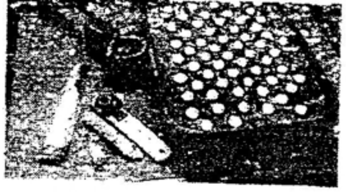

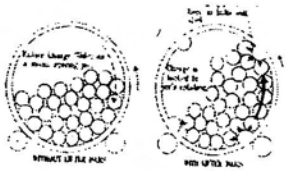

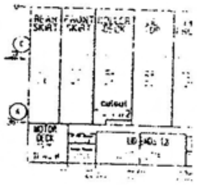

Ball Milling

Theory and Practice

for the

Amateur Pyrotechnician

By Lloyd E. Sponenburgh

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Ball Milling Theory and Practice
For the Amateur Pyrotechnician

A booklet covering theory, mill construction, and milling applications

Lloyd E. Sponenburgh

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To my lovely wife, Linda:

Mere booklets normally don't merit dedication pages. This is for the months of clanking and banging she put up with, for all the charcoal footprints tracking my travel from workshop to refrigerator, for all the muttering at the word processor, and for all the trips "for just a slightly larger pulley". She patiently built this mill, as much as if she had made all the parts herself.

Table of Contents

Preface vii

A Disclaimer and Warning ix

Part I -- The theory and practice of ball milling

The theory and practice of ball milling 1
- Some science in a black art 1
- Some terminology 2
- A list of mill features for a good mill 2
- An evaluation of commercial mills 3

How ball mills work 5
- Some method and myth 5
- A list of unknowns 5
- The world, according to manufacturers . 6
- The principal of cascading 6
- Speed formula for fastest milling 8
- The action of lifter bars 9
- Optimum material charging rates 9
- Various media charging rates 10
- The answers to our unknowns 11
- Considerations for building a mill 13

Part II -- Construction of an inexpensive, efficient mill

Construction of a mill 15
- A ball milling *system* 15
- Features of this mill 16
- Skills required to build the mill 17
- Limits of safety of amateur equipment ... 17

Tools list for building the mill and accessories.. 18

Materials list for the mill and variants 19

Materials list for home made grinding media .. 20

Materials list for milling jars 20

Materials list for a separation sieve 20

Issues dealing with various materials 21
- Where to find them 21
- Plywood and particle board 21
- Equipment rollers, bearings, and shafts 21
- Motors and wiring 22
- PVC fittings for milling jars 22

Issues dealing with assembly methods 23
- Layout and cutting 23
- **Layout sheet 25**

Beginning Construction 27
- The assembly process, cabinet assembly . 27
- **A CAD overview of the cabinet** 28
- Mounting the motor 29
- Mounting the drive components 30
- **The roller deck layout 31**
- Finishing up; the longest step 32
- Optional sound-deadening 34
- **The finished mill 35**

Constructing Mill Jars 37
- The debatable need for lifter bars 37
- How to safely cut large plastic pipe 37
- Jar lids, and clamping methods 38
- **Universal Jar Design 38**

Casting Lead Milling Media 39
    The dangers inherent in metal casting 39
    An unique way to make molds 39
    Method # 1 39
        A batch of molds, ready to pour . 40
    Method # 2 41
        'clipped' media 42
    Thirty pounds of media and a 6" jar ... 42

Building a Separation Sieve 43
    Pleating and fastening the sieve screen ... 43
    The sieves as media washers 44
    The screen and the finished sieve 44

Part III -- Using your new mill

Another safety lecture 45
    On the advantages of lids, and the disadvantages of losing a finger 45

Milling Mechanics 45
    Media slippage, lifters, and charging 45
    Jar failure mode 46

Milling Times 46
    'Popular' times vs. this mill 46
    Wear imposed by over-milling 46

Milling Temperature 47
    An experiment in controlling temperature .. 47
    72-hour meal, a thing of the past? 48

Media Selection 48
    Hardening of lead 49
    A selection criteria list 49

Media for mixing 50
    Optimum charging rate for mixing 50

Selection of a milling site 50
    Noise - Not in *my* shop 50
    Fire and explosion risks 50
    A custom, remote milling site 50

Physical Dangers of the Mill, Itself 51
    A way to help mitigate those dangers 51
    Interlock switches for safety.................. 51

Static Electricity Problems 51
    PVC as a tribo-electric generator 51
    Effects of a closed system 51
    The author's opinion 52
    A need for more research 52

Safely Emptying Mill Jars 52
    Breathing protection 52
    Stirred, not shaken 53
    Funnels help 53
    Screens do wear out 53

Milling Metals 53
    What media to use 53
    Is it cost-effective? 53

Part IV -- Improvements to the mill

Improving your mill after it's built 55
    A Thermometer 55
    A Thermostat 55
    A Timer for automatic "remote" on/off 56
    Quick-release Jar lids 57
        A quick-release design 57

Credits --

    Corporate assistance 59
    Personal assistance and thanks 59

Tables and Illustrations

Illustrations

Milling Terminology (inset) 2
Cascading Action, figure 1 7
Lifter Bar Action, figure 2 9
Layout Sheet for Plywood Cutting, figure 3 25
CAD Rear Skeleton View of Mill, figure 4 28
Motor Mounting photograph, figure 5 29
Roller Deck Layout, figure 6 31
Completed Mill photograph, figure 7 35
Universal Mill Jar Design, figure 8 38
Media Casting Tray photograph, figure 9 40
Finished Media and Jar photograph, figure 10 42
Separation Sieve photograph (2), figure 11 44
Quick Release Jar Lids contribution, figure 12 57

Tables

Jar Speeds in R.P.M., table 1 8
Media Charging Rates, table 2 10
Tools Recommended, list 18
Materials for mills, list 19
Materials for media, list 20
Materials for jars, list 20
Materials for sieves, list 20
Milling Times, text table 46
Table of Credits 59

Ball Milling Theory and Practice for the Amateur Pyrotechnician

Preface

This booklet is the product of a research effort I started because I personally wanted to understand ball milling. Once I had studied how industry uses ball milling, it became apparent to me that I could build a mill which would compete in performance with commercial mills. I did.

I was surprised at the interest it created in the amateur pyrotechnic community. The first two treatises in this booklet were published (in four parts) in *American Fireworks News* and the Florida Pyrotechnics Arts Guild club organ *1st Fire*. Subsequently, I received numerous calls and letters from readers and from people who had missed the articles, and wished to obtain reprints. Those people, and several professional pyrotechnics vendors encouraged me to make the articles available in the form of a short booklet.

To make the booklet commercially attractive, I've taken some liberties that magazines cannot afford: I've made all the photographs and drawings full-size (often full page), to more clearly show details. I've added a section about actual use of the mill. I've added some information about design changes and enhancements you can add to the basic mill design. And I've added some suggestions provided by readers of the original article.

Additionally, this booklet is bound in a lay-flat comb so that you may more conveniently use it in your own shop. A number of readers of the original articles have built mills from the design presented here; all have expressed satisfaction, and even downright *enjoyment* they've had from the improvement it afforded their pyrotechnic efforts. I hope you experience the same results.

Lloyd E. Sponenburgh, author
Member of F.P.A.G. and P.G.I.

Direct inquiries and comments by electronic mail via the Internet to

lloyds@fiscalinfo.com

or through the vendor from whom you purchased this booklet.

Warning and Disclaimer

The potential for misuse of the mill you can build from these designs forces me to publish this disclaimer:

The mill depicted in this booklet is distinctly 'amateur' and 'experimental' in construction; It was designed to be easy to build, and to perform well. However, those design targets can and probably will compromise the safety of the mill, if it is not used with proper care. The mill uses pulleys, belts, rollers, and motors, any or all of which can injure the operator. It is up to the builder to ensure that all working parts of the mill are adequately covered to prevent accidental injuries. It is up to the operator to ensure that all such covers are in place and functioning properly before operating the mill.

The mill could be used to pulverize materials which could ignite and/or explode from sparks or the forces and friction imposed by the milling itself. **You should not mill such materials. If you choose to ignore this caution, injury may result. The operator should avoid using jars or grinding media for combinations of chemicals which are known to be friction or impact sensitive, and should avoid re-using jars or media for other chemicals, when incompatible chemicals have been ground with them earlier. Especially, the operator should never use any jar or media which has ground chlorates to grind any other chemicals, whatsoever, and should avoid contamination of chlorate jars with other chemicals. Other chemicals may manifest mechanical sensitivity, as well. The operator is responsible for determining such sensitivity, and making certain that such chemicals or mixtures are not ground in this mill.**

The nature of this mill is both 'amateur' and 'experimental'. The author assumes no liability, express or implied, for the nature of the mill, or any potential hazards in its use. All liability resulting from the use of this mill lies with the individual who constructs or uses the mill. Do not allow minors or other untrained people to use any mill constructed from these designs.

If you do not feel that you can build and operate this mill safely, do not attempt to construct it.

- The author -

The Theory and Practice of Ball Milling

Some science in a black art.

Thirty-three years ago, when I had just become involved in pyrotechnics, I reckoned that there *must* be a better way to reduce chemicals to powder than mortar and pestle. I didn't know there was already such a device suited for amateur use. So I crudely built then what I now recognize as a **ball mill**. It didn't work very well, and it didn't process much material at one time. But it offered an improvement over hours of hand grinding.

Grinding chemicals to reduce their particle size is the foremost reason pyrotechnicians use ball mills. There are other uses; ball mills lend themselves well to mixing and drying operations, too. But size reduction is nearly always why a beginning pyro builds his or her first mill.

Once you decide to build a mill, it soon becomes apparent that there are many opinions on what makes a good mill. Everyone seems to have a different opinion about how ball mills work. Everyone, that is, except the folks who manufacture them.

Manufacturers of ball mills agree both on design and principals concerning the operation of their mills. Across manufacturers, mills look, act, are 'charged', and run nearly exactly alike. Amateur pyrotechnicians can gain from that knowledge.

An amateur pyrotechnician's first ball mill isn't likely to be a very good mill. It's likely to be inefficient. It will probably grind materials slowly, and be noisy and power hungry. It's bound to be pretty inconvenient to use, too.

These potential deficiencies root in the fact that a lot of the information we exchange about ball mills is conflicting or incorrect. Unless you're lucky enough to have access to a well equipped chemistry or biology laboratory, you probably haven't used a well designed mill suited to small-scale pyrotechnic use. Many pyros have never seen a good ball mill before they decide to build one.

Certainly, I had never seen a good mill. Because of the conflicting information available, I decided to research the subject. I discovered that ball mills play an important part in our lives.

Most people use ball milled products - paints, inks, medicines, insecticides, and more. Also, ball mills play an important behind-the-scenes role in our craft; fine-mesh metal powders are manufactured by milling, and most of our chemical suppliers seem willing to supply pre-milled materials. Since ball mills are common in industry, and since manufacturers are very concerned with cost and efficiency, I was sure I'd find a real science underlying their use.

The research went quickly, and rewarded me with opinions and designs which were consistent among several manufacturers. Some companies even supplied me with technical literature and illustrations. What they showed me was a well developed, well documented, and mature technology built more around accumulated experience than theory, but with enough real engineering to keep it out of the category of "black arts". This is a report on what works best for the type of grinding we do, *according to the experts in the field*, and how to build a *really good*, convenient, and efficient mill yourself.

"Time-Out" for a little terminology.

Small capacity mills are called "lab" or "pilot" mills, and the type of mill where free containers roll on powered rollers are called "jar" mills; their containers are called "jars". The balls and cylinders of metal or ceramic used inside the jars to do the actual grinding are called "grinding media". The mass of grinding medium and material to be ground is known as "the charge", with the mass of balls known as the "medium charge", and the mass of material to be ground known as the "material charge".

What constitutes a good mill?
A good ball mill should:

- Grind ingredients quickly and to small particle sizes
- Be easy to load and unload, and not messy
- Handle 'normal' batches
- Require little maintenance and few repairs
- Conserve power and grinding media
- Be relatively quiet

In addition to those performance criteria, a mill should allow our grinding more than one material at a time; that is, a mill should accommodate more than one jar at a time. The grinding jars should be inexpensive enough so that we can dedicate special ones for grinding materials like chlorates. And the cost of startup should fit within an individual's hobby budget.

The first question I asked was, "Will a commercial mill fit these requirements?"

Certainly, most commercially-made laboratory and pilot jar mills will meet all of the performance criteria I listed. But they miserably fail the cost criteria, both for initial setup, and for the cost of jars. An ordinary price for just one 1-1/2 gallon grinding jar for a commercial mill is - brace yourself - over $600. That doesn't include the mill, or any grinding media. A typical mill in a size suited to amateur pyrotechnics costs over $1000. "Rock tumbler" type mills are less expensive, but don't work well for grinding powders. They are designed to operate very slowly, and with different amounts and types of charges than ball mills.

Well, that seems to point us more or less *directly* to the "build it yourself" option! If we're going to build our own mills, we need to know how and why they work. What follows is the detail of what my research into ball mills dug up. I'll finish by giving you details and measured drawings for building your own ball mill of commercial efficiency and capacity, but at a fraction of the cost.

How ball mills work

method and myth

Ball mills work by allowing 'balls' of heavy material to fall upon and crush the material being milled. Repeating the action hundreds or thousands of times results in reducing the material to a fine powder. A traditional ball mill does the 'repeat' action by enclosing the whole working mass - balls and material being processed - in a drum, and rotating the drum so the contents are tumbled over one another continuously.

That's pretty simple. All that's left is:

- what size 'balls'?
- what weight 'balls'?
- should the 'balls' be *balls at all*?
- how far should they fall?
- how fast should they tumble?
- what should they be made of?
- how many of them?
- how much material per load?
- what shape container (jar)?
- how large should the jar be?
- how big a motor to turn it?
- can I afford this?
- can I **build this myself**?

We get lots of advice from each other, and some from literature. In *Pyrotechnics*, Weingart recommends building a ball mill from a 50 gallon wooden barrel, with 100 lb. of 1" lead balls for the grinding medium. In this, he grinds about twenty pounds of meal powder *by cranking the barrel by hand*! Ooof! That sounds like hard work. And ball mill manufacturers show us that his proportions of capacity vs. material charge vs. media charge are all off-kilter. He had about four gallons of material to grind, and about 1-1/2 gallons of grinding medium in a 50 gallon barrel. Keep those figures in the back of your mind while we take a short excursion into ball-milling theory.

The world, according to ball mill manufacturers

Some pyrotechnists believe a mill works most effectively when balls fall freely from as high as possible onto the balls at the bottom. Doing so, they strike one another with great force, and will pulverize very hard materials. This does work best for certain materials, like metal powders, where a "stamping" action is desired. But for general milling, ball mill manufacturers do not recommend this "free-fall" method.

First, since there is only one primary impact for each ball per revolution of the jar, only a tiny amount of material actually gets crushed. Milling is extremely slow. Also, the medium and jar can suffer excessive wear because of the force of the impacts. Mill manufacturers recommend, instead, what's called a "cascading" action.

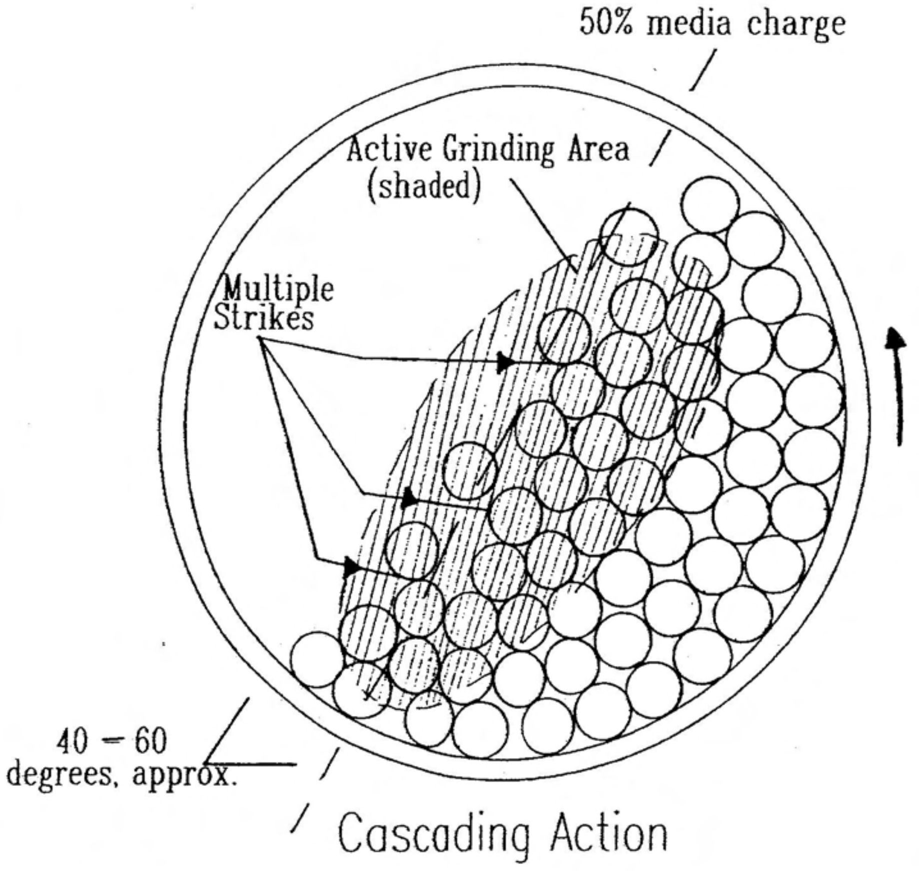
Cascading is a waterfall-like action where a continuous, fluid sheet of balls and material fall from the top of a pile down a slope to the bottom of the jar. In order to maximize the force with which the balls strike one another, the distance the balls fall should be maximized. This is done by filling the jar 50% full of medium. All manufacturers agree that this amount, known as **the medium charging factor** should vary but slightly, because it offers the longest path from the top of the heap of medium to the bottom. Also, the slope of the heap should be as steep as possible, consistent with keeping the balls each striking several other balls on their way down the slope.

It's this **multiple strike** action where each ball strikes several others on the way down that permits rapid grinding. This grinding action is not reserved to only the surface layer of material. There is a diminishing grinding effect extending to the center of the charge, shown by the shaded area within the charge in **figure 1**.

The "slope" of the pile is known in construction trades (where material just sits still, in heaps) as "the angle of repose". In milling, where things are constantly moving, it's known as the **angle of break**. The optimum angle of break of the heap is about 40-65 degrees from horizontal. At this angle, balls fall hard and rapidly, but do not break free of the pile to fly to the bottom without hitting others. The correct angle of break may be maintained by a couple of methods.

The angle of break will change as the speed of rotation of the jar changes. The slower the rotation, the shallower the slope of the pile. If the jar turns too slowly, balls will simply slide down the sides of the jar, failing to pile up enough to cascade. This causes extremely fast media and jar wear, and is usually manifest by grooving on the inside of the jar, and flat spots developing on the balls. But the jar can spin too fast.

Figure 1 - Cascading Action



As the jar rotates faster, a speed is reached where the balls actually centrifuge away from the pile, and fly free, without cascading. This speed is called **the critical speed** of the jar, and is calculable for a specific jar diameter and ball diameter. It *does not vary* for different media weights, like lead vs. ceramic balls, but does vary for different ball diameters. Some critical speeds for various jars and media are given in **table 1**, along with the formula for computing the critical speed.

Table 1 - Jar Speeds in R.P.M.

Jar Dia.	Ball Size	Critical	Optimum
6"	1"	119	77
6"	1/2"	113	73
5"	1/2"	125	81
4"	1/2"	142	92

Optimum RPM is 65% of Critical Speed

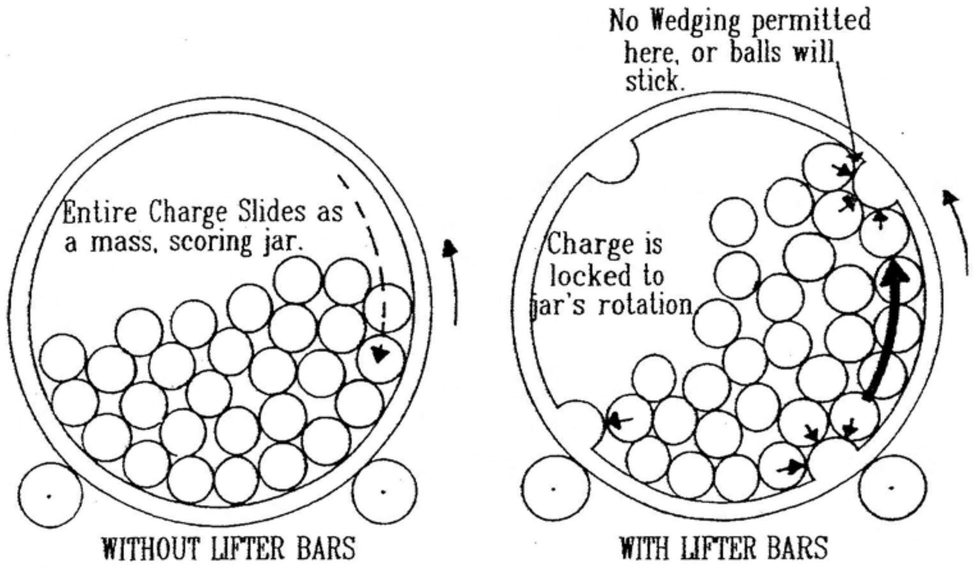
$$CS = \frac{265.45}{\sqrt{(jar\_i.d." - ball\_o.d.")}}$$

The optimum speed of rotation for a jar is from 45% to 110% of the critical speed, with the variations being caused by factors like the viscosity of the material being ground, and the material itself (how much force is required to grind it). For dry powders, a speed of 65% of the critical speed for the jar/medium is just about perfect. But sometimes, the balls will slip down the jar sides without reaching the desired angle of break, even when the correct speed is maintained.

To prevent the charge from slipping, **lifter bars** are mounted longitudinally in the jar. Lifter bars are very low in height, usually less than one ball-diameter. They are fashioned more like low ribs than paddles, for it is not their purpose to lift and propel balls to the top of the jar. Rather, they serve to "lock" the entire mass of medium and material so that it cannot slide down the side of the jar.

Once the charge is locked to the jar's rotating speed, it can cascade properly. But it cannot grind material unless there is material between the balls when they strike one another. If there is too much material present, it will serve to cushion the blows, and reduce the grinding action. Apparently, there must be an optimum **material charge**.

Figure 2 - Lifter bar action


No Wedging permitted here, or balls will stick.
Entire Charge Slides as a mass, scoring jar.
Charge is locked to jar's rotation
WITHOUT LIFTER BARS
WITH LIFTER BARS

The ideal material charge is dependent directly upon the **medium charge**, which is, in turn, determined directly by the empty capacity of the mill jar. A mass of balls constitutes a mass which is about 60% solid, and 40% space between the balls. If we just ***exactly fill*** these spaces with material to be ground, the balls will be touching (and striking) one another with, on average, *no material between the striking surfaces*. Actually, random actions in the jar will allow some material to be ground, but most of it will seek the available space between balls, and not be ground effectively.

To effectively grind material, we need just enough material covering the striking surfaces so grinding will occur with every impact, yet not enough so that cushioning of the strikes occurs. There is an optimum amount.

The optimum material charging factor for dry grinding is about 25% of the empty jar's volume. At this charging rate, the spaces between balls are just barely overfilled, but not much extra cushioning material is present.

It can be difficult, sometimes, to determine exactly what is the ideal amount of dry ingredients, because some materials, like "stick" charcoal, compact a great deal during the initial phases of grinding. For ingredients with odd initial shapes or mixed "chunk" sizes, rough reduction to uniform particles should be done before final ball milling.

With charcoal, for instance, it's beneficial to break up the sticks to 8-10 mesh before ball milling. A ball mill will break up large chunks, given time, but you run the risk of ending up undercharged, and you may have to add more material during the grind to get the best and fastest grinding action. Wet ingredients are easier to charge, because all of the spaces between particles are filled with fluid, so it's easier to judge volume.

A rule of thumb for wet milling is to cover the grinding medium completely to a depth of one ball diameter. Wet media charging rates can vary from dry rates. Some dry charging rates for various media are listed in **table 2**. This table gives the amount in pounds of medium per gallon of empty mill capacity in order to achieve a 50% fill. This table is best used when purchasing media. For filling, a table is unnecessary; you can just measure the mill's empty capacity, and use half that much medium. With a mill rotating at about 65% of the critical speed, these charging rates assure maximum grinding speed with minimum jar and medium wear. Experts agree, also, that there is no advantage to running different-sized balls in a jar; all balls should be the same size.

Table 2 - Media charging rates

Medium	Spec.Grav.	Charge/gal
porcelain	2.38	6 lb.
high alumina	3.30	8.5 lb.
zirconia	5.50	14 lb.
Burundum(tm)	3.42	9 lb.
steel	7.85	20 lb.
lead	11.35	29 lb.

Charge based on 50% of jar volume.

Burundum is a trademark of Norton Abrasives.

Looking back briefly at Weingart's meal powder mill, we can see that it was drastically undercharged, both with medium and material. He had the respective proportions of medium and material reversed from what would have worked best. And he had (or at least expressed) no idea concerning the most effective speed to crank the mill. The information wasn't generally available (at least, to pyrotechnicians) when he wrote *Pyrotechnics*.

To design a good mill and properly charge it, we need to answer the whole list of unknowns encountered earlier. We've answered most of the list by now:

- what size 'balls'? All balls should be of the same size. The smaller the balls, the more surface area per gallon of medium, and the more surface area, the faster the grinding action. Balls between 1/2" and 1" in diameter are best for most of the sort of grinding we do. The real issue is whether or not the balls are heavy enough to crush the chemicals we grind. For a mill larger than 4" in diameter, 1/2" steel balls are heavy enough to grind rapidly. Ceramic media work well in 5"+ mills.

- what weight 'balls'? The material should be as heavy as possible, consistent with a hardness sufficient to do our grinding but not wear too rapidly. Burundum, zirconia, high-density alumina, and just plain, white porcelain balls are all heavy enough to grind pyrotechnic chemicals in ball sizes over 3/4" in diameter, and jar sizes over 5" in diameter. For smaller mills, or smaller balls, lead or steel balls should be used. Many pyros prefer lead balls, because they will not spark; but some fear that lead will wear off into the material.

A properly designed and charged mill will wear the drum and media only very slowly; media wear, even with lead balls, should not be a worry. Antimony hardened lead offers advantages over softer, pure lead. Soft lead will dimple, and limit the fineness of grind. The dimples "hide" pockets of unground material from strikes which would reduce the material, if it was exposed. Harder balls do not dimple as badly.

- should the 'balls' be *balls at all*, or some other shape? Besides the sphere, another popular shape for ball milling media is the "radiused-end cylinder". It occupies about the same solid-volume in a mass as spheres, and offers a little more surface area per volume. So, it grinds just a bit faster. Radiused-end cylinders are usually more expensive than spherical media, and not tremendously more effective. There is, however, a "hidden" advantage to cylindrical media which we'll discuss in connection with building a mill.

- how far should they fall? A six inch inside-diameter mill (gross volume about 1 gallon) is about right for a lot of amateur work. A six-inch mill will grind about two pounds (1kg) of dense material like potassium nitrate (1lb / pint liq. vol.). Remember that a mill and the medium can be damaged by under charging. If you do a lot of formulation experiments, you need to build some smaller mills. A five-inch mill will grind about a pint of material. A four-inch mill will grind about a cup of material. For a given volume, the efficiency - the grinding speed - increases with the mill diameter. A one gallon eight-inch diameter mill will grind faster than a one gallon six-inch mill, since the balls have further to fall. A four-inch mill will grind a cup of material more slowly than a six-inch mill will grind a quart. The balls have further to fall in a larger mill. They make more strikes per revolution, and thus, do more work.

- how fast should they tumble? Dry grinding should be done at about 65% of the critical speed for the jar and medium you're using. Use the table or formula to determine the critical speed for any particular jar/medium combination.

- what should balls be made of? alumina, Burundum, steel, lead. The choice is centered around weight and hardness. Antimony hardened lead is heavy enough and hard enough for most pyrotechnic purposes, but high-density ceramic media are easier to clean, and grind somewhat finer. Ceramic might spark, lead will not. Oxidizers will corrode some metal media.

- how many of them should there be? For dry grinding, there should be enough balls to fill the mill to 50% of its empty capacity.

- how much material should be processed at a time? Twenty-five percent of the mill's empty capacity. If the medium is 40% voids, then a mill 50% full of medium will be 20% full of voids between the balls. A material charge of 25% will fill all the voids, plus just a little to insure that every impact crushes material.

- what shape (and material) should the container (jar) be? The jar may be octagonal or cylindrical. Cylindrical mills may require four lifter bars bolted equidistant around their inside surface. For a six-inch mill, a typical lifter bar would be as long as the cylinder is long, and about 1/2" square, with its exposed upper edges rounded slightly to prevent them from chipping during milling. They may be made of the same material as the jar. Lifter bars may not be necessary, if the material, charge, and jar speeds are all correct.

Commercial jar mills are made of highly abrasion-resistant materials, like alumina or abrasion-resistant steel. They don't have to be. If we assume that the jar might be "disposable" in the long-term, then cheaper, easier-to-machine substances are available. PVC pipe can be made into an excellent, durable mill.

- how large should the jar be? Six inches in diameter by eight inches long will accommodate about two pounds of material per grind, for dense substances like potassium nitrate. Smaller sizes can be readily built for smaller batches. Remember, charging is by *volume, not weight,,* so a given volume mill will grind less weight of a less dense material.

- how big a motor will it take to turn it? Ah! Horsepower! This is something we haven't even touched upon yet. The volume of a cylindrical mill increases with the square of the diameter. The power required to turn it increases at the 2.6th power of the diameter...... That's all true, but it boils down to this -- a 1/4 horsepower shaded-pole motor (like used for fans) will turn a two-jar mill, but cannot start it without assistance. A capacitor-start motor with its higher starting torque is what's called for. A 1/2HP "washing machine" motor (capacitor start) offers enough torque to start a fully-loaded two jar mill without any help from the operator. Such motors are ordinarily *less* expensive than 1/4HP motors (available new for under $50), and can be had at many surplus firms for pocket change.

Now you know what the manufacturers of ball mills say works the best.

Next, we consider building a mill:

- can I afford this? Oh, YES! If you stick to the plans in part two of this booklet, the entire mill can be assembled from inexpensive stock components and readily available raw materials which will require little or no custom cutting or machining. If you're an active "do it yourself-er" you may have everything you need already. In that case, all you'll have to buy is the grinding medium. And if you're willing to alloy and cast your own lead media, you may not have to *buy* anything.

- can I **build this myself**? Yes, you can. No special tool skills are necessary. Critical dimensions are resolved by the design itself, so you don't have to be a machining genius. It will be easy to charge, and easy to unload, and it will be clean to use. When you finish, you'll have a mill which will both look good and operate like a commercial mill. You'll have a mill to be proud of, and one which will make your pyrotechnics hobby more productive and enjoyable.

Read on -- Next, we'll build a mill.

Part Two -
Construction of an inexpensive, efficient ball mill

In part one of this booklet we explored the theory and practice of efficient ball milling. This section describes in detail how to build an attractive, efficient, and inexpensive ball mill that is well suited to small scale pyrotechnic use. I will present diagrams, photographs, and measured drawings to build a mill that is part of a **ball milling system.**

A *system? A* mill only grinds material. After it grinds, you must separate the material from the grinding medium. You also require grinding media. This milling system includes solutions for all three issues. This system is meant for amateurs -- but who wants to waste time?

The mill depicted here will compete effectively against commercial ball mills for grinding efficiency. In tests of this mill, milling times called out in amateur formulae were reduced by at least a factor of four; "overnight" air-float charcoal may be produced in two to four hours. Two-hundred mesh willow mills in less than forty minutes. Potassium nitrate prills mill to -100 mesh in under thirty minutes. One pyrotechnician produced some fast 75-15-10 meal (which, when granulated, was faster than Goex FFg) in *under three* hours! Really. The first time you use an efficient mill, you'll be astounded at how fast it works!

This mill is inexpensive, not *cheap.* If you buy the plywood and rolling parts, and use a "found" motor, it can be built for as little as $65. Its cost fits well in the category of other permanent pyro tools, like rocket tooling and presses. It is designed to be a high-performance, permanent addition to your pyrotechnics workshop. This is not a trivial project. Depending upon your woodworking experience, expect to spend from three to five busy evenings building the mill.

Please, don't be put off by the scale of this project. Your milling requirements may not be ambitious. I've kept that in mind, and made the mill design *scaleable.* Working from really raw material forms requires a lot of milling. If you make your own charcoal, or use fertilizer grade chemicals, you need a fast, capacious mill. If you don't mill a lot, please read on. This mill can be scaled in size and capacity to exactly suit your needs. You may even choose not to build this mill, but make it the basis for your own design.

That's good; the mill's design is the product of evolution. Many pyrotechnicians have contributed to its form. I've contributed a number of design features to the evolution.

If there's anything unique about this mill, it's these things:

It's efficient.
When built carefully, it's a really attractive addition to your shop.
It is a completely designed system with measured drawings --
You don't have to *invent* anything to build this mill.
You can build any one of the models or variants from the one cutting layout.
Only straight cutting is required.
All joinery is butt-joined, using screws and glue for strength.
The design controls most critical dimensions.

The design manages all the dimensions except for the moving parts layout on the roller deck. The design even acknowledges some unknowns.

You'll find "junk" motors in a variety of sizes. This design will accommodate a motor of unknown size and rotation direction. A simple mounting system allows you to easily adapt motors of various diameters and lengths for use. You can build this mill in several variations.

You'll be presented with a single design which allows you to build one of two basic models -- free standing or table-top. You can build it in one of two sizes -- a one-jar or two-jar model. You can make one of two versions -- with or without a noise-suppressing cover. The mill will handle one-gallon, half-gallon, and one-quart milling jars without modifications -- the roller assembly is adjustable. Choose what you need.

The two-jar free-standing model is an imposing piece of not-very-portable furniture. The one-jar tabletop mill is a small, portable shop accessory. You can make exactly what fits your situation. You'll need some accessories, too.

You'll be shown a sieve capable of holding over thirty pounds of mill contents without collapsing. You'll find out how to prepare your own very inexpensive milling media. That is the only task here which requires *some* special skills to do.

To cast your own lead milling media, you'll need a melting pot, ladle, source of heat, suitable protective clothing, and **experience**. I consider metal casting tools to be 'special' because most home shops don't have them, and you cannot buy them at an ordinary home center. Leave the actual *pouring* task to someone with experience casting metals; it's dangerous.

DON'T try melting lead in a coffee can on your stove, or with a propane torch. It's a process fraught with danger, and one that is likely to get out of control easily and quickly.

Just as using flash powder is considered to be the "high casualty" activity of pyrotechnics, so is casting metals to the do-it-yourself shop. You can buy grinding media, or you can prepare the molds, and let someone with experience do the casting.

Pyrotechnicians have better-than-average tool and material handling abilities; it's a requirement of our craft. The design presented here presumes that you have some basic tool and woodworking skills -- no special skills. To build one of these mills and its accessories, you'll need to be able to:

- cut a straight and square line in plywood with a circular saw,
- drill a straight hole, and
- measure and mark parts placements accurately.

Please remember this: **This mill is specifically designed to be easy to build, and to be efficient. Like much 'amateur' equipment, it does not have all the safety features you normally would find on commercial mills. If you cannot operate this mill cautiously and safely without those features, you should not build it, or should equip it with such features yourself. Any machine with motors and moving parts can be dangerous to the operator -- this mill is no exception.**

Lists of tools and materials and brief discussions about them follow. The rest of the article will read as an assembly process, rather than a narrative. I know you want to build a mill, not just read about it!

Please read and understand the entire process before you begin to assemble your mill. It's also a good idea to have all of your materials on hand before starting, so you can confirm clearances and fit as you proceed.

Tools Recommended --

Hand-held circular saw with a fresh blade.
Hacksaw with 18 tooth-per-inch blade
3/8" Electric drill, Variable Speed and Reversible is desirable
#2 Phillips bit to fit chuck of drill, or #2 Phillips screwdriver
5/32" Allen (hex) wrench
3/32" Allen wrench
Utility knife
Scissors
Bicycle air pump, compressed air supply, or a nearby service station
Tape measure and good ruler/straightedge for marking layouts
A square
Awl or prick punch, *very* sharp
wire strippers (motor wiring)
long-nosed pliers (motor wiring)
Twist drill bits - 3/32", 9/64", 1/4", 5/16", 3/8"
5/8" wood bit - a twist drill will not do, a spade, brad-point, or Forstner is O.K.
110 degree countersink bit (cosmetics, only)
1/2" combination (mechanic's) wrench or small Crescent wrench
7/16" combination wrench
Fine-toothed metal cutting (mill) file or bench grinder
Sander or sanding block with sandpaper grits - 80, 150, 220
disposable paint brushes
caulking gun
a small hammer

To cast lead media:

Fire gloves, facemask, plumber's apron, and heavy brogans.
A melting pot with heat source,
A plumber's ladle (1 lb. is a good size)
A propane or acetylene torch (in addition to the melting pot heater)
A sand tray, or 10" x 14" baking pan filled 1" deep with clean, ***dry*** sand or clay kitty litter

To build a separation sieve:

A Pop-Rivet tool
tin snips
1/8" drill bit

Materials list, MILL -

† f or one-jar models

‡ for lidded models (for reasons of safety, you should build a lid)

	1	- 4' x 8' sheet , 3/4" 5 or 7-ply plywood	
	1	- 1/3 to 1/2 HP Capacitor-Start, 1725 rpm, 115v motor w/ 48 or 56 style mount. Serv-S-Line 5KC40GT36S, Grainger # 6K758 (no mount - cheap!)	
RK11 9.95 13¾ x 1½	2 († 1)	- 14" x 1-1/2" ball-bearing equipment rollers with mounting brackets, Crawford WM-21, Home Depot —	Wood Workers 761-4402 -
	1	- 34-5/8" (†18-3/4") x 5/8" round steel bar stock	893-0015
15¾ x 2 PVC	3 († 2)	- Dayton 5/8" self-centering ball-bearing pillow-block bearings, Grainger #2X898. These are *light duty* bearings. 8.16	800 mai
	3'	- 5/8 i.d. x 7/8" o.d. Automotive Heater Hose, LifeLine UPC #038244168583 , Pep Boys Auto Parts	
	2	- 26" x 2.00 bicycle inner tubes, K-Mart	
	4	- 1" diameter table leveling feet with threaded shanks and threaded leg inserts, Shepherd #9450 (4 per pack), Home Depot	
	4	- 1" diameter TEFLON adhesive-backed furniture slides, MAGIC SLIDERS brand (as seen on TV!), Home Depot	
	12 (†6)	- inches VELCRO hook and loop adhesive-backed tape, 3/4" wide	
	100	- 2" drywall screws	
	6	- 1-1/2" drywall screws	
	12	- 1-1/4" drywall screws	
	12	- 3/4" x #6 sheet metal screws, Phillips pan head - OR	
	6	- 8-32 x 2" bolts and wing nuts to match (for mounting the rollers adjustably)	
	1 ‡	- 30" continuous hinge, Stanley # 70-0360, Home Depot	
	2 ‡	- chest latches, Stanley #80-1700	
	1 ‡	- sliding lid support, Stanley #80-1525 (7-1/2")	
	1	- 6" o.d. x 5/8" shaft sheave (pulley) , Grainger #3X919	3.72
	1	- 2" o.d. x 1/2" shaft sheave, Grainger #3X895	
	1	- 24" x 3L form-factor drive belt, Grainger #3L240	
	6	- sets - 5/16" x 1-1/2" carriage bolts, flat washers, split lock washers, and nuts	
	4	- sets - 1/4" x 1-1/4" carriage bolts, flat washers, split lock washers, and nuts (if needed for mounting motor)	
	1 qt	- clear lacquer sanding sealer	
	1 tub	- wood filler putty	
	8 oz	- yellow wood glue (1- 8oz bottle)	
	1 tube	- construction adhesive (Liquid Nails ®) (optional)	
	2	- 2' x 4' sheets of 5/8" cellulose acoustic tile (optional)	

Materials list, GRINDING MEDIA-

30 lb.*- lead (*for each gallon of empty jar capacity)
up to 16% Antimony metal (optional)
1 - roll, 27 square feet, heavy duty aluminum foil
6 - inches of 3/4" hardwood dowel

Materials list, JARS -

"Combination" blade for circular saw.
Some scrap 2x8 lumber, 2 pcs about 12" long.
Some scrap 1/2"-3/4" plywood, 2 pcs 10" x 10"
PVC primer/cleaner and heavy-duty cement, and

For each jar (6", 5" , or 4" size),
1 - square (flat bottomed) end cap
optionally, round-end caps can be used, and three rubber stick-on "feet" can be affixed to the jar bottom to make it sit stably on a flat surface.
1 - reducer (6" to 4", 5" to 3", 4" to 3")
1 - pc PVC pipe (8" of 6" pipe, or 6" of 5" pipe , or 5" of 4" pipe)
1 - Schedule 40 rubber test cap with clamp (4",3",3")
4" jar may require special clamp, see text.

Materials list, SEPARATION SIEVE -

2 - Five-gallon plastic buckets which will nest.
The top one should have a lid.
1 - 18" square of 4 mesh hardware cloth.
16 - 1/2" grip-range 1/8" aluminum pop-rivets
with two washers for each rivet.
12 - 3/4" pan head wood or sheet metal screws
2 - feet scrap 1x2 or 2x2 lumber

Materials issues

Where:

Home centers don't all carry the same brands, so I'm supplying the telephone number of the company which makes the one critical part you may not be able to buy locally. Crawford Products, Inc., Hanover, Massachusetts makes the rollers. They invite inquiry at 1-800-225-5832. Another brand of similar rollers is Eagle brand rollers from Woodworkers' Warehouse (known in some areas as Trend-Lines tool company). Grainger outlets are in nearly every large and medium-sized city. Look them up in the yellow pages. They may require a 'company name' in order to deal with you, since they are a wholesale dealer.

Plywood:

Please don't use particle board. It won't last under vibration stress. I've had a number of particle board mills disassemble themselves during use! Additionally, particle board is moisture sensitive, and will swell in high-humidity environments.

Rollers:

Make sure they are really ball-bearing rollers. They should be about 2" high at the top of the roller, and must be under 15" long at their outermost dimensions. Such rollers nearly always come with dry bearings. You must lubricate them before use, and every few hours of operation thereafter with 10W machine oil like "3-In-1" brand. The recommended inner-tube roller covers will greatly quiet your mill, and extend jar and roller life, but they are not absolutely necessary.

The 5/8" rod:

Check it carefully for straightness before you buy. It's nearly impossible to straighten a crooked piece. Roll it on a flat surface, and check for "wobble". However, don't get fooled by a little "burr" on the rod end which causes it to roll unevenly. Most such rods are "snipped" off longer stock, and the cut is not smooth. It might cause you to reject a rod which is otherwise OK. Cold-rolled bar stock, or "drill rod" is superior to hot-rolled stock, which has a bad finish.

Bearings:

NEVER tap, hammer, or force bearings on or off a shaft. Bearings cannot withstand forces other than in the bearing plane. Forcefully installing bearings will damage them. If they don't go on easily by hand, the shaft either is too large, or has a burr on the end. The 5/8" steel rod specified may not be a perfect fit. Sand, sand... One shaft I made required about 1/2 hour of sanding with 80-grit paper before the bearings would slide on (with a little friction, but not great force).

Motors:

You will probably use your mill at some time to grind meal powder. When using it for such duty, it's advisable to start and stop the mill remotely. A 1/4-HP shaded-pole motor doesn't have enough starting torque to start the fully-loaded mill without help. A capacitor-start motor, with it's higher starting torque is what's called for. Generally, the cheapest motors in that class are 1/3 to 1/2 HP washing machine/dryer motors. Most such motors don't have their own mounting brackets, so you'll have to clamp them to the motor mounting base with metal straps. I mounted mine with four dabs of RTV Silicone glue between the motor and the motor-mount, and with two 12-ga steel wire "leashes" around the mount rings. It holds as securely as a commercial mount; see the pictures. The recommended motor cost me $57, new.

wiring note - the listed motor has no diagrams with it; it was intended as a "replacement" motor. Mine wires pins 5 and 6 of the start-switch together to the "hot" lead, and pin 1 to common. The motor frame should be attached to ground. This motor is listed as a capacitor-start motor, and has the starting torque needed -- but no capacitor is needed nor used in its intended clothes-dryer duty. There are no diagrams with the listed motor, but the pin numbers are clearly marked on the motor frame.

You may use either a CW or CCW rotating motor (clockwise or counter-clockwise, viewed from the pulley end) . The design favors CW rotation. Rotating that way imposes most of the weight and vibratory loads on the strong, cushioned pillow-block bearings, instead of the less durable roller bearings. That makes for a longer-lasting and quieter mill. If you cannot find a CW rotating motor, consider "flipping" the roller deck design end-for-end. If your motor has a 5/8" shaft, Grainger stocks sheaves for that size. The pulley ratio recommended will spin all three sizes of jars at acceptable speeds; it's optimized for the four inch jars. The design presumes a motor outside diameter less than seven inches.

PVC pipe and fittings:

I chose thinwall pipe (type #3034, or sometimes called "Schedule 35") over heavier pressure piping for several reasons: It's much less expensive, it's lighter and easier to cut, and schedule 40 rubber test caps will fit snugly over a thinwall fitting of the same nominal size. If you use thicker pipe, the caps will not fit over the fittings. In that case, simply add to the neck of the jar a short "stub" of the correct pipe. The caps are actually designed for fitting directly to a bare pipe.

The thinner-walled jars are somewhat noisier than their Schedule 40 counterparts, but seems to hold up fine in milling duty. Use good quality neoprene test caps, not the cheap vinyl ones you may find at a discount home center (bend them, then *smell them*. Vinyl has a characteristic odor like a new shower curtain. Neoprene smells like new tires). The vinyl caps may tear, spilling the mill contents. Five-inch fittings are scarce. Fortunately, I find that six-inch and four-inch jars meet most of my needs. **Be careful with thinwall pipe**; some fittings sold for thinwall are styrene, rather than PVC, and will not endure heavy milling. Very large pipe like this is often *not carried* by plumbing suppliers. Check with your local Septic Tank installation companies for materials. Avoid the *very thin* black-lined sewage pipe as unsuitable.

DON'T try to cut PVC pipe with a circular saw until you've read the precautions, and understand the method completely -- it can hurt you! Thin materials tend to snag, bind, and splinter when being cut.

Flat-bottomed end-caps are desirable, because jars made with them will sit upright for filling. But round-end caps can be pressed into service, too. To use them, stick three rubber "chassis feet" on the rounded end in such a pattern so that the jar will sit stably upright. If you do use round caps and rubber feet, you may have to slightly shorten the jar length to allow it to fit between the jar stops (not if you build the mill to the dimensions supplied), and you may have to add some spacers behind the jar-stop "buttons" so the button can contact the base of the jar without permitting the rubber feet to strike the jar-stop vertical members. If you very carefully place the chassis feet on the jar so that the rounded bottom of the jar *almost touches the surface* the jar sits on, then you probably will *not* have to add spacers to the jar-stops. The furniture slides used as jar-stop buttons naturally protrude from the jar stops by about 1/4".

Laying out and cutting:

Unless you do a lot of woodworking, it's not immediately obvious that you cannot cut two twelve-inch widths from a two-foot-wide piece of stock. Consider; the saw doesn't just part the pieces of wood, like a knife. Rather, it removes some of the material. This removed stock, called a "kerf", averages about 1/8" with common circular saw blades. You must allow for it when marking and cutting your plywood. That's why the cumulative measurements on the cutting layout I've provided don't add up to the total of the widths of the pieces.

If your saw blade cuts a narrower kerf than 1/8", you'll find the pieces all end up a bit too large. You can either sand them to size, or carefully adjust your assembly so that the larger pieces fit square -- either will work. You can also adjust the layout to fit your blade. Most carbide blades cut 1/8" kerfs. Plywood blades make a narrower cut.

The way I've measured, **all cuts should be to the right or to the bottom of all marking lines.** Use a fine-point pencil to mark your lines, then cut, "letting the line stand". That means cutting as close to the line as you can while still allowing the mark to remain. The ideal cut would be with exactly half of the pencil line remaining after the cut. Also remember that cutting and marking errors can be cumulative. That means it's a good idea to mark the entire layout before you begin cutting, rather than using a measure-cut-measure-cut system. The latter almost guarantees out-of-square work, even if you accurately cut the pieces to size. Make all measurements from the left and top edges of the plywood. Factory-cut plywood is accurate in straightness and square. You can use its edges as references. However, it is *not always exactly 48" x 96" in size.* That's why you should always measure from one, factory edge.

Study the layout sheet on the next page (Figure 3). Be sure you clearly picture where all the cuts go relative to the markout lines. Mentally step through the cutting schedule, and make sure it's clear how you'll proceed.

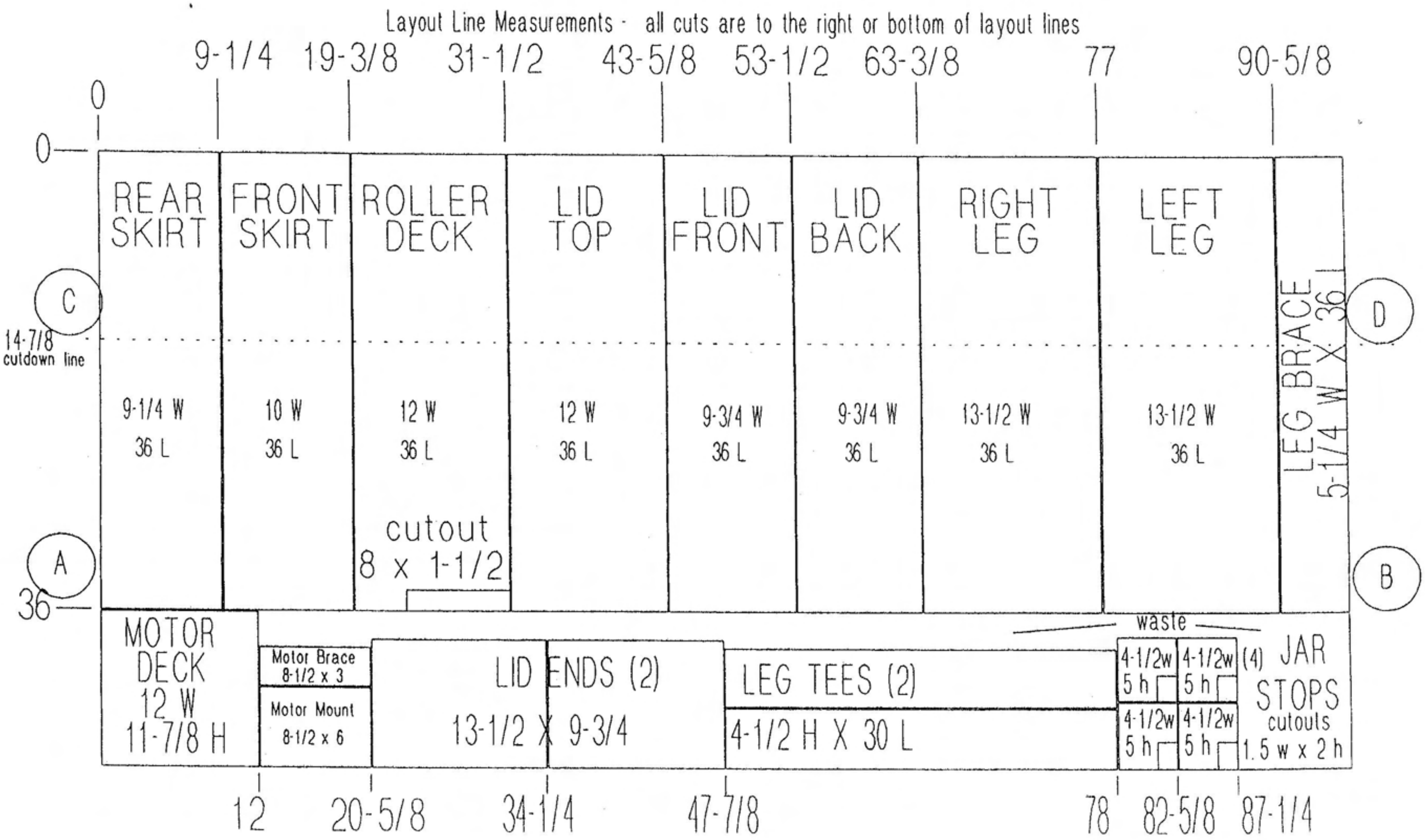


Figure 3 - Layout sheet for cutting plywood

Figure 3 is printed separately on this sheet for easier reference while building the mill.

Building the mill

1). Decide which model you'll build, and obtain your materials.

2). Review the cutting layout, and mark your plywood for cutting. Labeling the pieces will help during assembly. Check all the lines for square. Make sure you clearly envision all cuts going to the right or bottom of the layout lines.

3). Cut all the plywood to size. Make the major cuts in the following order:

Cut the long line A-B, which yields one piece 36" wide, and one piece 11-7/8" wide.

If you are building the one-jar model, cut line C-D, which shortens all the case parts to 21".

Cut out all the individual parts, remembering to cut to the right or bottom of each layout line.

Make the five "inside" cutouts; one in the roller deck and one in each of the four jar stops.

In *every case* where a hole is called to be drilled, measure and mark the location carefully with a pencil. Make a small starter hole precisely on the mark with your awl before attempting to drill. The starter hole will prevent your drill bit from drifting off the mark. Your awl should be needle-sharp, or *it* will drift. I haven't marked the screw holes on the pattern, except for those in the roller deck. Elsewhere, use one screw for every six inches of joint, and space them in a pleasing manner. Place the holes so each screw centers in the edge of the panel it joins . Pre-drill (pilot) your screw holes to minimize 'split-out'.

4). Fit the lid pieces together upside-down on a flat work surface, and pre-drill all screw holes with the 3/32 bit to 1/4" less than the full depth of the screws. With the 9/64" bit, enlarge the screw holes in the front and back where they attach to the top, and enlarge all the holes in the ends. Counter-sink all the holes so the screw heads will tighten flush with the surfaces. Assemble the lid without glue. Tighten the screws only lightly; they must be removed later.

5). Assemble the mill cabinet the same way as the lid, upside-down on a flat surface. This is the time to "flip" your roller deck if you're using a counter-clockwise rotating motor.

If you're building the table-top version of the mill, cut the legs down to 10" long. Attach the ends or legs to the roller deck just as the lid ends attached to the lid. Drill and countersink all the holes, and assemble the mill cabinet without glue.

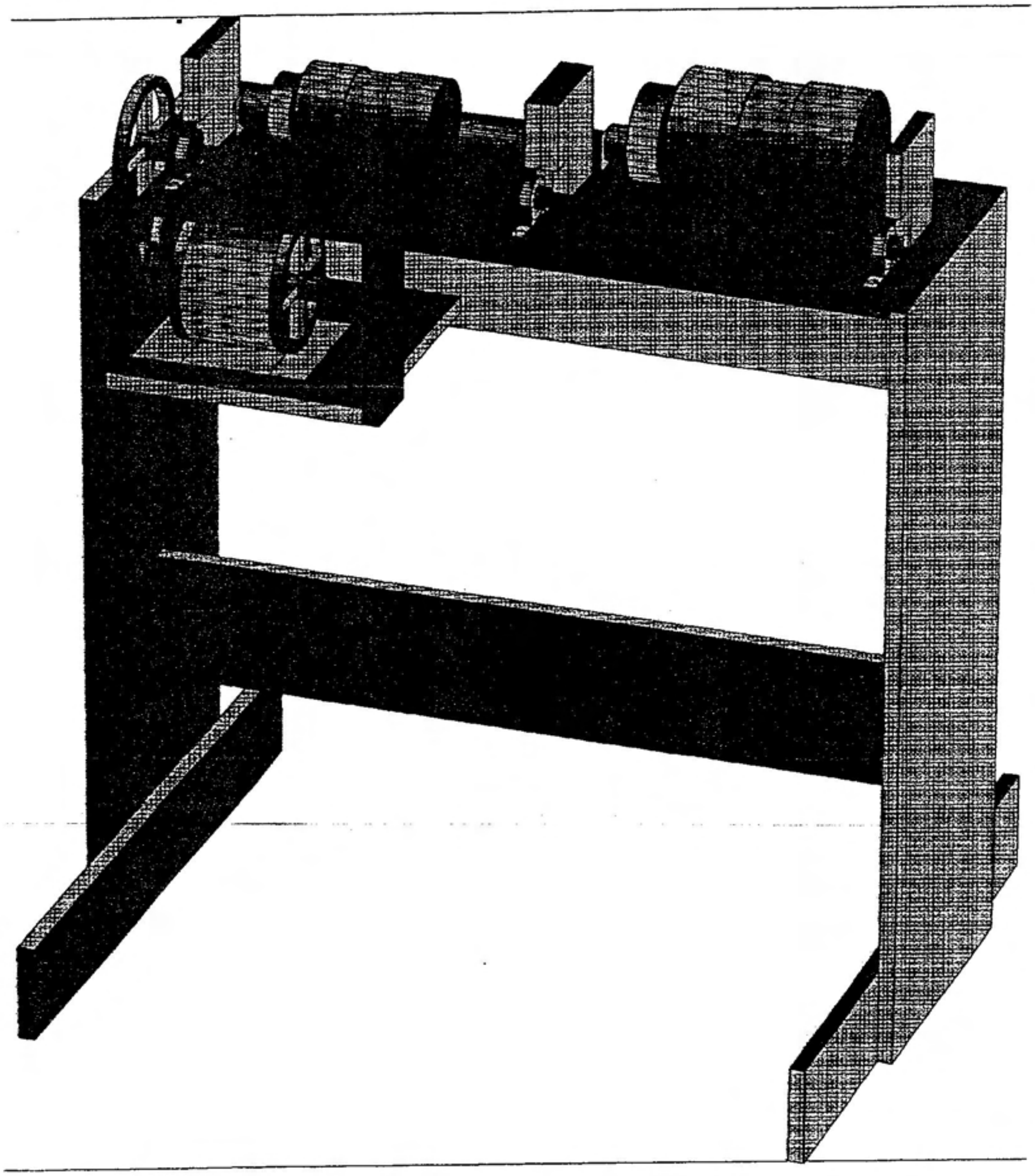


Figure 4 - CAD rear skeleton view showing motor deck and brace.

6). Still with the mill cabinet upside-down on your work surface, block up the motor deck into place at what will become the bottom of the cabinet when it's flipped over. Note carefully that the motor deck mounts flush with the bottom of the rear skirt, but sits up (down, in this position) from the bottom of the front skirt by 3/4". The gap in back is to provide motor ventilation for the table-top model. Drill and countersink the motor deck's screw holes, and drive the screws. Attach the motor deck brace at what will be the rear inside corner; follow the same drilling, countersinking, and fastening method as before.

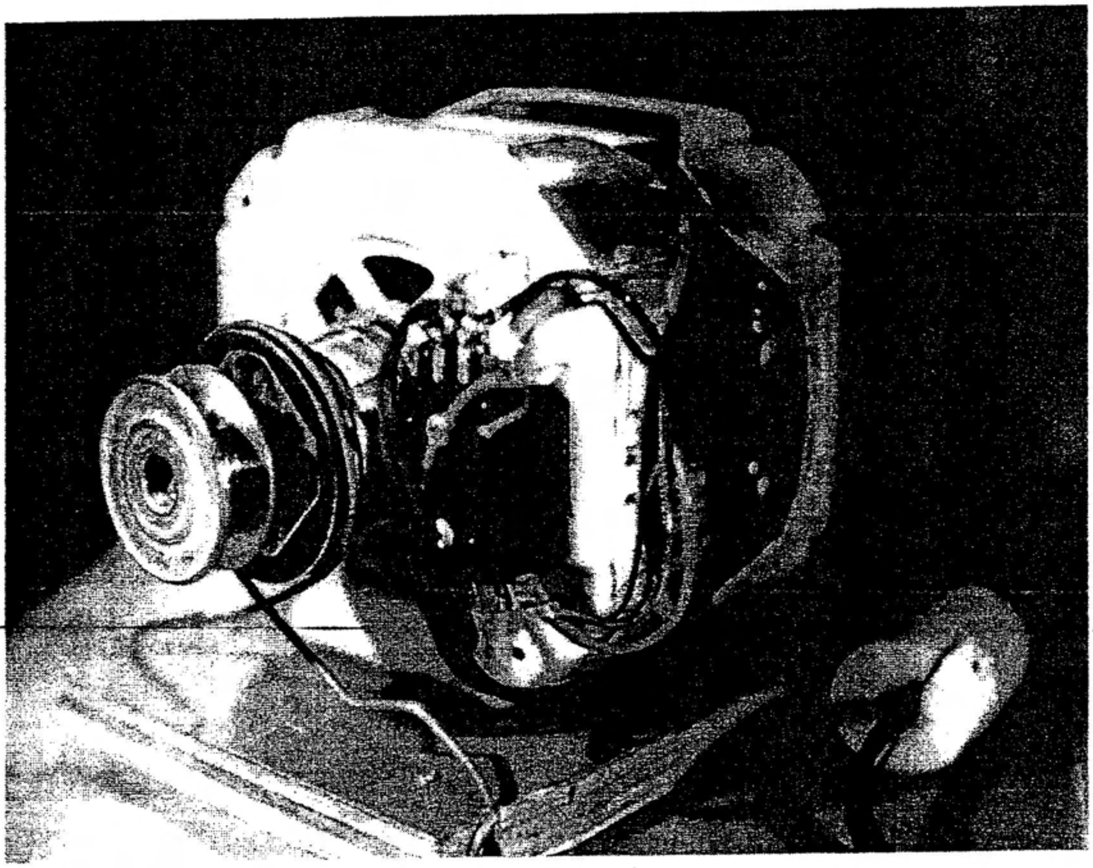


Figure 5- The "cheap" motor and improvised mount. Note Z-bends to tighten wire after attachment to base. (Just grip wire with pliers, and *twist)* RTV silicone glue fastens the motor to the wooden base. The rear of the motor also has a wire leash, which is hidden in this photograph.

7). Place the motor centered side-to-side on the motor mount, and with the shaft protruding about 1" past the edge of the plate. If you're mounting your motor with the carriage bolts called out in the plans, countersink the holes with the 5/8" spade bit *before* you drill them through with the 1/4" bit. The bolt heads should not protrude past the bottom surface of the motor mount; the motor mount must lie flat on the motor deck when placed there. Install the 2" sheave on the motor shaft with the hub placed toward the motor, and the motor shaft's end flush with the outer side of the sheave. Tighten the sheave setscrew with the 5/32" Allen wrench. Set the motor assembly aside.

8). If you're building the free-standing model, attach the leg brace now. Drill the leveler insert holes 2" from the ends in the bottoms of the leg tees with the 3/8" bit. Install the levelers. Attach both leg tees with six 1-1/4" screws each, checking with the square to verify that they are exactly perpendicular to the legs. Again, assemble with no glue.

9). Turn the mill cabinet right side up and lay out the drive shaft bearing locations. Note -- measure the layouts from the rear edge of the roller deck, not from the rear edge of the rear skirt. Also note that the bearing locations are measured from the far right edge of the deck, as **if the pulley cutout had not been made.** The jar stops should mount just "inside" the edges of the bearings for each jar position so the jars will hit the stops before any part of them hits the bearings. Only the lid support holes are measured from the left edge of the deck.

Drill the pillow-block mounting holes with the 5/16" drill. Press the bearing-mount bolts into their holes from the bottom. Seat them firmly. Finally, level the cabinet on a solid floor.

10). Cut the 5/8" rod down to the 34-5/8" or 18-3/4" length with the hacksaw, and chamfer the cut end. (Caution! Read the materials notes about forcing the bearings, if you haven't already). Temporarily slide all of the bearings onto the 5/8" rod stock. Note the orientation of the bearing hubs. Install the 6" sheave on the motor end of the rod with the hub toward the bearings, and the shaft (rod) flush with the outer face of the sheave. Firmly tighten the sheave setscrew with the 5/32" Allen wrench. Place the pillow-block bottom channels on the mounting bolts, rest the shaft bearings on the channels, and place the top retainer frames on the bearings. Lightly tighten all the nuts holding the pillow-blocks.

Note: The pillow-block mounts have elongated holes to permit your adjusting the mounting position. Make sure the shaft is *exactly parallel* to the rear edge of the roller deck when the nuts are tightened.

Check the shaft for binding. If it binds, the roller deck may be warped. Straighten it, if necessary. This might require loosening all the fasteners on the deck, and also those attaching the deck to the cabinet. It might even involve

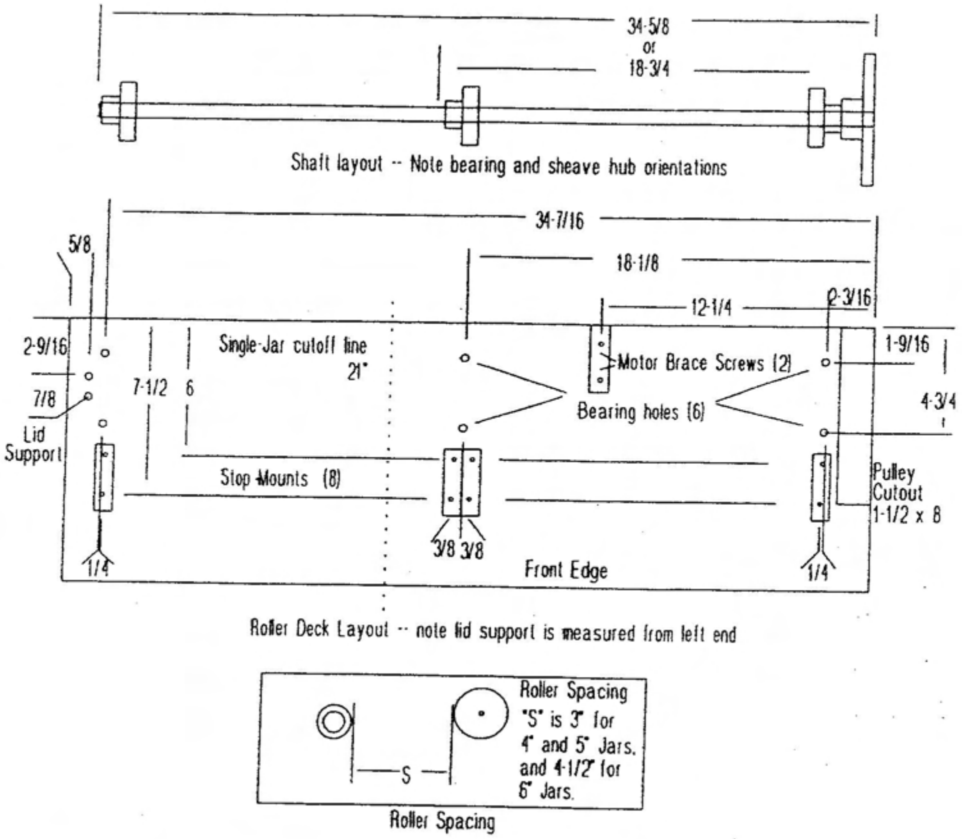


Figure 6 - Roller Deck layout

drilling *new holes* for attaching the deck to the cabinet. It really pays to be careful the first time.

11). Mark and drill the jar-stop mounting holes from the top of the roller deck with the 9/64" drill. We'll mount the jar stops during the re-assembly phase after finishing the cabinet. We won't mount the roller assemblies until after the jar stops are attached. For now, verify that the rollers can fit completely between the jar stops and parallel to the drive shaft without interference. Lay out, drill, and countersink the holes for the motor deck brace. Drive the brace screws.

12). Position the lid on top of the cabinet and check for fit. If necessary, adjust its fit with sandpaper or saw. Tape the lid in place with masking tape around the joint. Position the hinge centered and square along the joint between lid and rear skirt, and pre-punch a hole for each screw with the awl before driving the screw. Mount the latches on the front of the cabinet. Remove the masking tape, and check the lid operation. Take care not to let it fall or it may tear out the hinge. Mount the lid support inside the lid at the end opposite the drive pulley cutout. Adjust its tension screw so it slides with a little friction.

13). Remove the rear skirt. Set the motor/mounting plate assembly onto the motor deck so the motor's sheave is directly beneath the 6" sheave. Run the drive belt around both sheaves. Slide the motor toward the front of the cabinet until the belt is fairly snug. Drive two 1-1/2" drywall screws through the bottom of the motor deck into the motor mounting plate, about three inches apart, and near the pulley end of the motor.. Make sure the belt remained properly tensioned, and the sheaves remained aligned with the belt and one-another. Re-install the rear skirt, and test the motor. The belt should not rub, slap, or bind. It is normal for the sheaves to get warm from belt friction; they should not get hot. Remove the motor after testing. Don't bother to reinstall the rear skirt.

The mill is built. The gluing and finishing are next. You'll install the jar stops during re-assembly, after the mill has been sanded and finished. You'll install the rollers after the mill is completely reassembled.

14). Remove all hardware before gluing and finishing the mill. Disassemble then reassemble the mill, this time with glue. **Do not glue the motor deck or rear skirt** - they should remain removable. Sand the mill cabinet, and finish with two or more coats of sanding sealer, sanding lightly between coats. Glue two of the jar stops together into a 1-1/2" thick stop. Sand, seal, and finish the jar stops.

15). Install a 15" piece of heater-hose on the drive shaft in each jar position. It's a tight fit! Make sure the bearing orientations remain correct. Mount the drive shaft onto the roller deck with flat and lock washers . Make sure the shaft is parallel to the rear edge of the roller deck.

16). Hold each jar stop squarely in position, and lightly mark holes in its bottom surface through the roller deck with the 3/32" drill. Carefully continue each hole to 1-1/2" deep. Mount all three jar stops without glue.

17). Mount the motor deck and brace without glue, except where the brace joins at its top end to the roller deck. Install the drive belt and the motor. Use six 1-1/2" screws evenly placed around the area of the motor mounting plate to fasten the plate to the motor deck. Reinstall the rear skirt. Reinstall the lid and its hardware.

18). Cut a gauge block from scrap plywood 3" wide by 4-1/2" long. Use the gauge to mount each roller in *each* of its two possible positions. The roller mounts 3" away from the drive shaft for 4" and 5" jars, and mounts 4-1/2" away for 6" jars. Make sure the rollers mount exactly parallel to the drive shaft.

Note: You may have to provide clearance for each roller shaft to slide out of its bracket when the rollers are adjusted to the 4"-jar position. Drill a 5/8" hole in the jar stop where the roller shaft would impinge if the stop interferes with your removing the roller from its mount.

Never place a six inch jar on rollers adjusted to the narrower position; It may jump off the rollers.

19). Stretch two layers of inner-tube rubber onto each roller --

Heh, heh! It's *impossible*, right?

Cut an inner tube about three inches from the valve stem. Tie each end of the tube shut with twine or a very strong rubber band. Tie it off as close to the ends as possible, so there isn't much waste beyond the knots. Inflate the tube until it resembles a three-inch diameter sausage about five feet long; don't inflate it any more than necessary - it should be a little soft. Now the trick -- *Push the roller into the end* of the inflated tube lengthwise until you've completely buried it about three inches past the rubber. With the scissors, cut the inner tube right where it doubles over, inside-out.

Voilà! You now have a roller covered in two layers of inner tube.

Cut the other end of the tube about two inches away from the roller, so you have a generous overhang on both ends. The rubber is now stretched, and will relax and pull away from the roller ends, so some excess material is necessary at first. Cover the second roller. Vigorously "massage" the rollers by rolling them on a smooth, hard surface. Let them rest for a few hours. Do this a couple of times before trimming the rubber to within 1/4" of the ends of the rollers. Re-install the rollers in their brackets. Trim some more if the overhanging rubber interferes with rotation.

Using rubber covers on the rollers is not necessary, but it makes the mill quieter, and helps reduce shock loads on the rollers' bearings. A warning, though -- If there are *any* sharp protrusions on the jar surfaces, they will rapidly 'eat' away the rubber covers. Your jars must be smooth and round for the rubber covers to last.

20). For one end cap from each size of PVC pipe, carefully mark its exact center on its outside surface. With the rollers properly positioned for that size jar, place the cap on the rollers in its "rolling" posture. Mark the positions on the jar stops where the center of the cap will make contact. Stick a 3/4" square of VELCRO loop tape at that location on the jar stop. Each end stop should have three squares of tape -- one for each jar size. The doubled center stop should have three squares on each side. Finally, stick a square of VELCRO hook material to each of four Teflon furniture slides. (Because the tape is narrower than the slide diameter, I used the slide's own adhesive disks *in addition to* the Velcro's adhesive).

When you mill, move the slides to the appropriate positions on the jar stops for the size jar you're running. They provide excellent, cushioned stops for the jars. You'll find that your jars always seek a particular stop when they roll. Turn your jars so that the PVC end cap bears on that stop, rather than the rubber test-cap. The rubber will tend to abrade slightly on the Teflon furniture slides. The PVC caps slide on Teflon with virtually no friction.

The mill is complete except for one optional addition. The design purposely leaves an inch of clearance between the lid and all moving parts except the 6" pulley. If you wish to further quiet your mill, line the insides of the lid, the bottom of the roller deck, and the insides of the mill cabinet with cellulose acoustic tile. You can cut it with a utility knife, and attach it with construction adhesive. **Do not place any tile directly over the motor.** The motor produces a lot of heat.

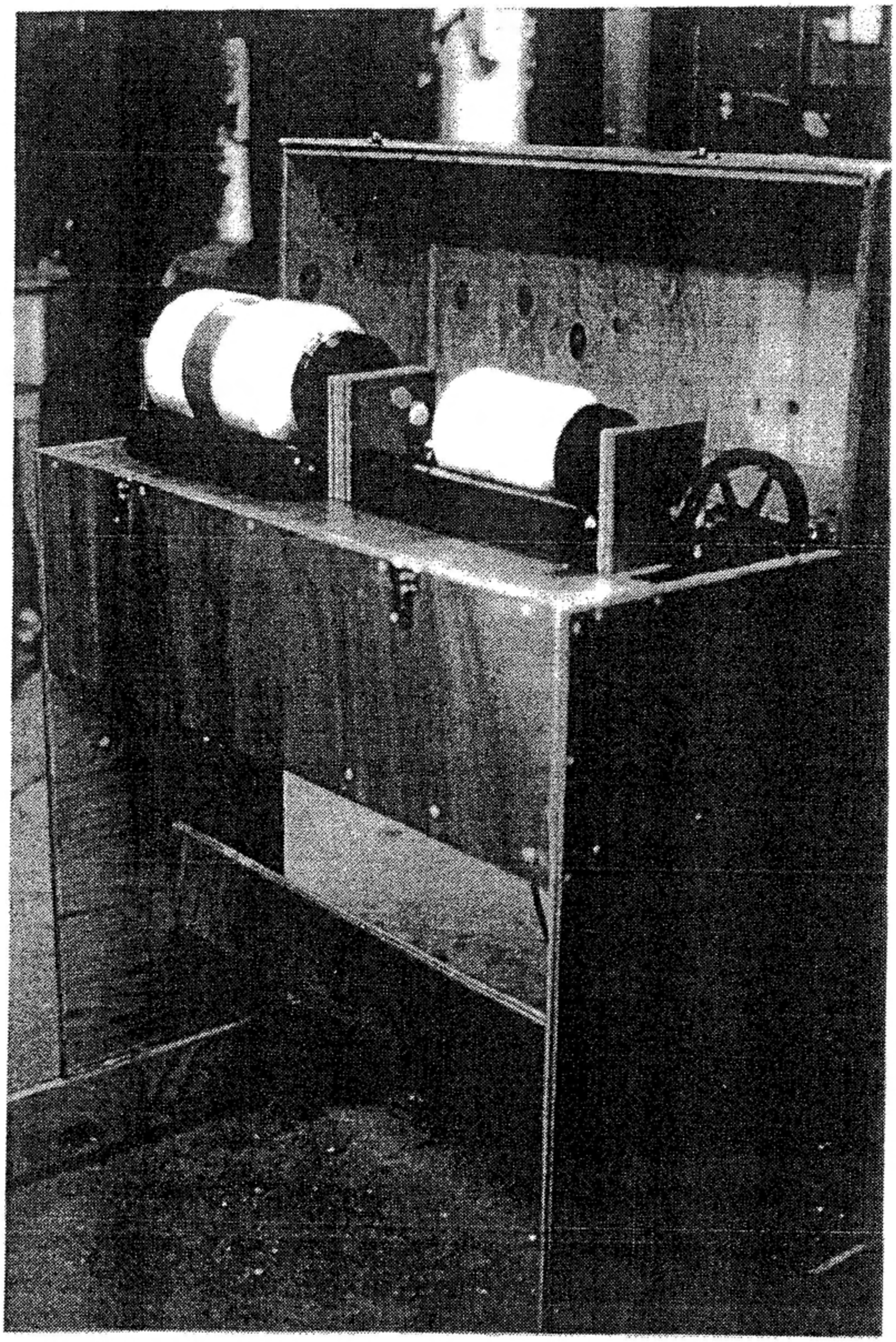


Figure 7 - The complete, two-jar, free-standing mill, with both 6" and 4" jars in use. Note the lack of a pulley guard. The *closed cover* acts as a guard. If you build a lidless mill, fashion a pulley guard out of thin plywood or sheet metal.

Constructing Mill Jars

Mill jars require no special skills to fabricate, but they do require some special techniques. It's very difficult to cut a piece of large-diameter pipe evenly and square. A circular saw will do it, but that introduces some special dangers. This technique will allow you to cut large PVC pipe safely with a circular saw.

Some good news! After lengthy testing, I can find no good reason to install lifter bars in these jars. The inner surface of PVC pipe is 'lumpy' enough so that the charge doesn't tend to slip. It may slip when wet milling. In that case, make some 1/2" x 1/2" bars of high-density polyethylene, and attach them inside the jars with counter-sunk wood screws, from the outside. Don't allow the screws to penetrate the bars all the way into the milling area. Make sure the screw heads do not protrude past the rolling surfaces of the jars. Use at least five screws per lifter bar; four bars per jar. If you make lifters from strips of PVC pipe, you may choose to glue them inside the jar with PVC cement. Seal any screw holes by filling the hole with rubber caulk before driving in the screw.

To safely cut pipe with a circular saw, build a "tunnel" from the 2 x 8 lumber and scrap plywood which is a close fit for the pipe. When you begin to cut pipe, **turn your blade around in the circular saw so it rotates in reverse.** That's right - *instead of cutting the pipe, you want the blade to "scrape" through the plastic.* A regular "combination" blade works better than a plywood blade - it doesn't overheat as easily.

Capture the pipe in the tunnel, then cut the pipe where it emerges from the end of the tunnel. The plywood "lid" on the tunnel provides the flat surface you need to safely guide the saw.

Enlist a helper to firmly hold the free end of the pipe. WEAR EYE PROTECTION. Cut firmly and deliberately, and do not dwell in the cut. The pipe can melt from friction heat.

Contact cement a sheet of 80 grit sandpaper to a 10" x 10" piece of plywood. Use this to flush-sand the ends of all the pipe cutoffs. This isn't absolutely necessary, but it makes the jars much easier to clean. In any case, clean the pipe of any burrs and shavings.

See figure 7 (pg 35) and figure 9 (pg 42) for photographs of finished milling jars.

Thoroughly clean all pipe ends and the insides of the fittings with cleaning solvent. Apply PVC cement generously to all mating surfaces, and quickly assemble the pieces, making sure you "bottom out" the pipe in each fitting. **After the cement has set, sand or file any bumps, logos, or casting defects off the rolling surfaces of the jars.** Fit each jar with a rubber cap and clamp. If the clamp is so large that it interferes with rolling on the smaller jars, you may simply *tape* the cap on with masking or duct tape, or fashion a lower-profile clamp from several smaller clamps connected in series.

One of the readers of the original AFN articles submitted an idea for a more refined jar cap which will not interfere with the rollers. That idea is included in the milling tips section (section 3) of this book.

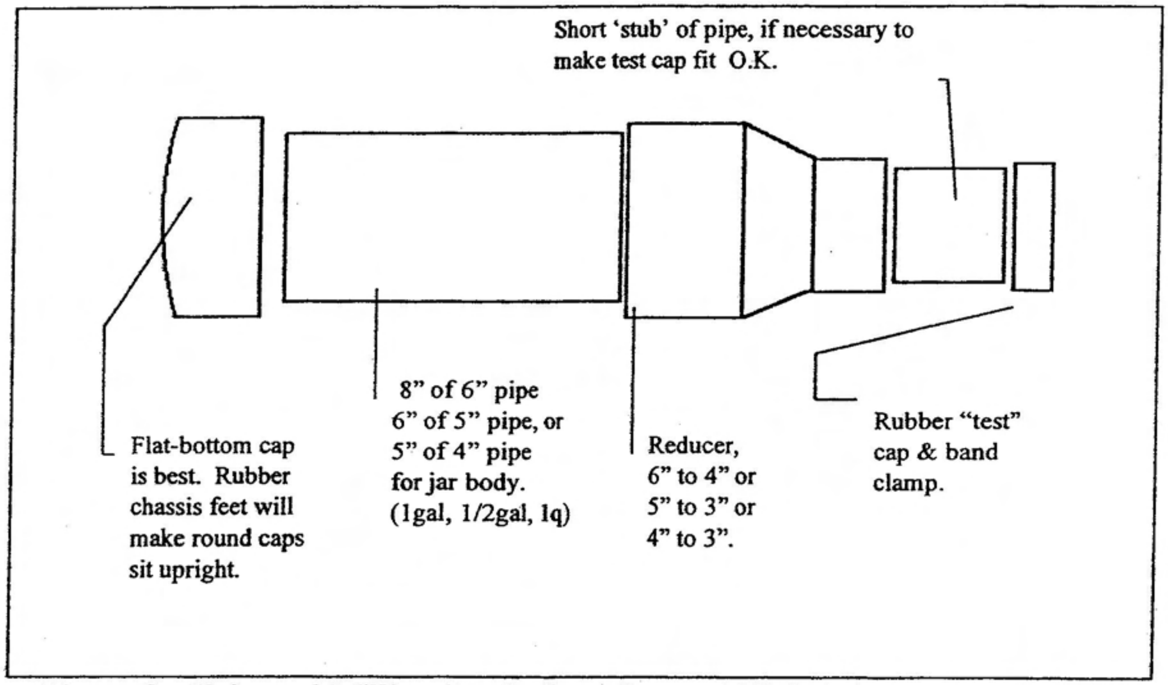

Short 'stub' of pipe, if necessary to make test cap fit O.K.
Flat-bottom cap is best. Rubber chassis feet will make round caps sit upright.
8" of 6" pipe 6" of 5" pipe, or 5" of 4" pipe for jar body. (1gal, 1/2gal, 1q)
Reducer, 6" to 4" or 5" to 3" or 4" to 3".
Rubber "test" cap & band clamp.

Figure 8 - Universal Milling Jar Design. Standard PVC fittings are used.

Casting lead milling media

Casting metals is dangerous. If you don't have experience, make up the molds, then seek a plumber or firearms reloader for assistance.

Scrap lead is nearly dirt cheap. I buy salvaged vent flashings from a local recycler for 25¢ per pound. However, lead isn't all you need. The most likely reason you can't cast your own lead media is lack of molds..

Two processes for easy mold-making follow: They are similar. One produces finished media which is smooth, completely formed, and perfect in appearance. But the method is tedious. The other method produces *really ugly* media which takes a couple of hours of milling to achieve its final shape and appearance -- but the method is easy. Take your pick. Either method produces media which is perfectly satisfactory for general milling.

Ball molds for black powder weapons are expensive, and they're not commonly available in sizes over .65 caliber. If you have a drill press and some large bits, you can easily make an aluminum mold for casting cylindrical media. But for those who don't have the tools, or don't feel qualified to build a permanent mold, I'll show you two simple expedients for making molds. This first method produces perfectly formed media, right from the molds. It's labor intensive, but no more so than rolling shots for crossettes.

Ah! There's the clue. If you can roll shot tubes, you can roll perfectly satisfactory molds for lead media. All that's required is a tube former and lots of pre-cut pieces of heavy-duty aluminum foil.

You can cut foil with scissors, but it's a thankless job. It's not effective to fold multiple thicknesses and cut them all at once; they tend to clinch together at the edges, and don't separate easily. Don't dismay; I've discovered a quick, easy way to cut them one at a time. Use one of those sewing accessories called a "rotary cutter". It's a circular knife blade on a shaft, and cuts as it rolls. Once you've used one, you'll never understand how you got along without it in pyrotechnics! It's wonderful for cutting paper.

Tear an 8" wide piece of foil from the roll, and spread it flat on the cutting surface. Using a 1-1/2" wide ruler or straightedge, cut 1-1/2" by 8" strips of foil. You can really move rapidly with the rotary knife. A one-gallon jar takes about 230 milling cylinders, so cut a bunch!

Prepare your former by sanding one end of the 3/4" dowel to a soft radius. You don't want a full spherical end; just "crown" it about 1/16". Sand the end of the dowel very smooth. Make a mark with a fine-tipped black marker all the way around the dowel 3/4" from the crowned end. Slightly whittle or sand down the other end of the dowel so it is still round but just a few thousandths of an inch under 3/4" in diameter. Crown that end with sandpaper also, trying for the same profile on both ends of the dowel. Finally, wax and polish the dowel. It should be slick and shiny.

Lay out a strip of foil on your rolling table, with the long dimension running fore and aft. Roll the foil onto the full-sized end of the tube former, with the whittled end pointing to the left. Keep the left edge of the foil aligned perfectly with the mark on the former. The foil should hang over the right end of the former by 3/4". Roll it tightly.

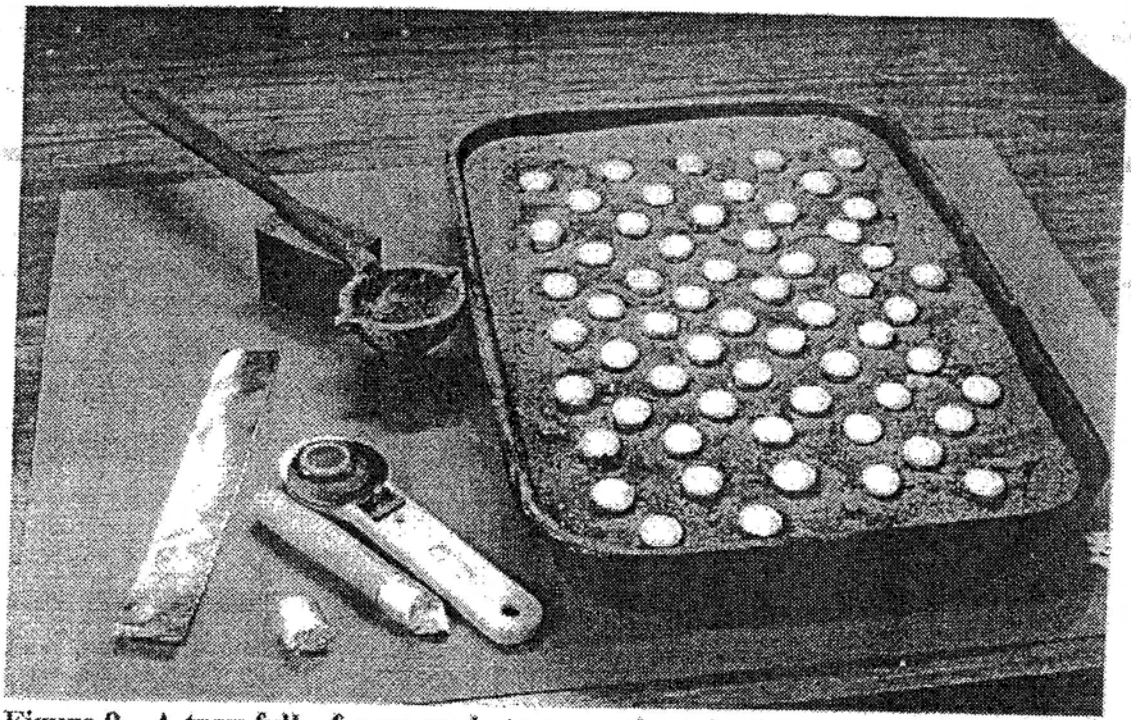


Figure 9 - A tray full of cups ready to pour, the tube former, and the rotary cutter.

Pleat the overhang, just as you would a shot tube. After pleating it, *press* it smooth and tight by pushing the pleated end down on the work surface, and "swirling" the top end of the dowel around. You should end up with a 3/4" deep, 3/4" diameter aluminum cup with a smooth, slightly crowned bottom. Gently slide the cup off the rolling end of the former. Slide it slowly, or the vacuum created will collapse the cup. Place the cup on the whittled end of the former.

Using that end as a punch, press the cup down vertically at least three fourths of the way into the sand in the tray. Be careful not to allow any sand into the cup. Don't put the cups *too close* to one-another, or the pressure from punching each cup into the sand will deform the ones near it. Repeat the roll-pleat-punch action until you've placed eight or ten cups. Prepare your molten lead, and have your hand torch at the ready. Consider adding up to 16 percent antimony to harden the lead.

Pour the cups full of lead. Pour right up to the top, but don't let the lead spill over the top edge. When the metal begins to freeze, you'll notice that it has shrunk drastically, and an ugly hole has formed in the middle of each pellet. Soon after the metal freezes, re-melt the top of each pellet with the propane torch, being careful to only heat until a uniform meniscus forms. Because the lead cannot wet the aluminum cup, the meniscus will be convex. The metal will re-freeze with a nice crown on top to match it's molded crown on the bottom. When the metal has frozen again, you may fish the pellets out of the sand with tongs, and place them aside on a heatproof surface to cool.

If you're trying to do more than eight or ten cups per tray, take care to point the torch *away* from any empty cups, lest you blow sand into them. Sand embedded in the lead media might cause sparks during milling. After the pellets have cooled, unwrap each one. I find it easier if I unpleat the ends first.

Media Casting Method #2:

Instead of rolling short, crowned tubes, cut the foil into 8" squares, and roll 8" tubes from the squares. Pleat one end of each tube, just like you would for the shorter ones.

Next, stand a few tubes at a time upright in a deep metal container (like a two-pound coffee can), and gently pour dry sand or kitty-litter around the tubes as you correct their stance. Be careful not to collapse the tubes as you pour the sand around them.

When the tubes are buried almost to their necks, pour each one full of molten lead. It will take slightly over one pound per tube. Don't worry about the shrink cavities which form in their tops.

As soon as the lead has frozen, remove the lead rods with tongs to a cooling area, and pour some more. Each tube will ultimately produce eight or nine milling balls. So expect to pour about thirty tubes for a one gallon milling jar.

After the lead rods have cooled, unwrap them, and clip them into 3/4" lengths with a pair of lineman's cable shears, or a pair of lever-action limb-loppers. Simply re-melt the portions which have shrinkage holes in them.

The 'clipped' media produced by this method has a lot of sharp corners, and starts out very ugly. But after a few hours of milling, it will be indiscernible from media produced by the cup-at-a-time method.

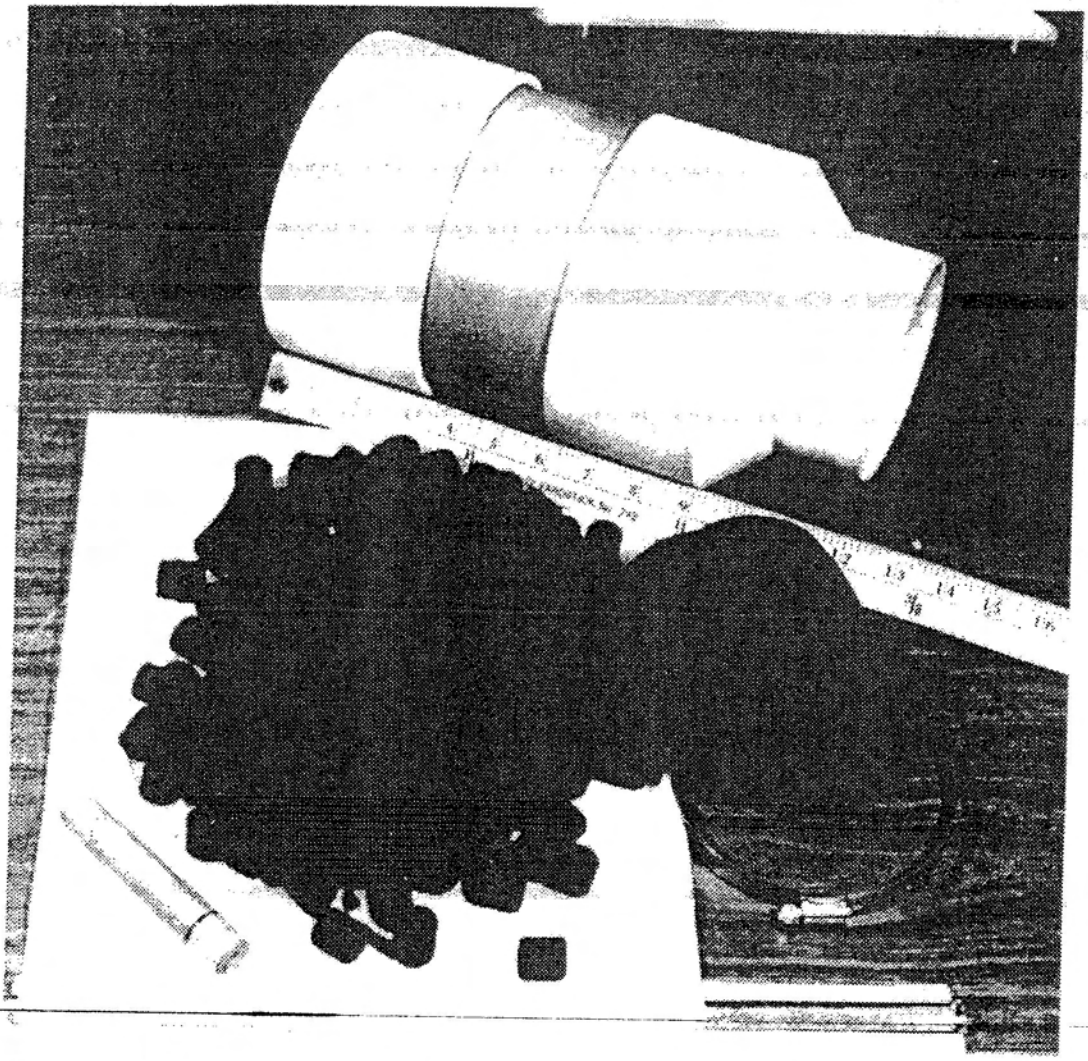


Figure 10 - Thirty pounds of lead cylinders, and a six-inch jar

Casting defects from folds in the aluminum foil will be beaten out of the pellets on their first use. Cylindrical lead media will deform with use, but if you charge the mill properly, they will not wear very rapidly. They will very slightly discolor white powders. Each 3/4" cylinder weighs about two ounces. Two-hundred-thirty of them together weigh about 29 pounds.

Building a separation sieve

Our milling system will be complete when we have a tool to help remove media from ground material. We need a separation sieve. The only problem is the weight of the mill charges.

A one gallon mill with lead media holds over thirty pounds of charge. That much weight will collapse many sieves. The sieve detailed here will stand up to the weight.

Obtain two five-gallon buckets that will nest without jamming. Cut the bottom off the "top" bucket. A saber saw with a fairly coarse blade is an easy way to do this. Clean up the rough edges with a knife. Center the cut bucket on the square of hardware cloth. Mark a circle exactly around the bucket. Mark another circle 1-1/2" further out. Cut the screen on the larger mark to yield a circular screen 3" larger in diameter than the bucket. Cut radially in from the edges of the screen just up to the inner circle, but not beyond. Make sixteen evenly spaced cuts, so the circle resembles a sixteen-petaled sunflower when cut.

Center the bucket on the screen, and pleat the petals up on the outside of the bucket. About halfway up each pleat, and centered side-to-side, drill a 1/8" hole through the screen and bucket *just under a screen wire*. Install a washer on a pop rivet, and insert the rivet through the hole from the outside of the bucket. Place another washer on the inside end of the rivet, and clinch the rivet, clamping the screen firmly to the bucket side.

Repeat this pleat-drill-rivet process all the way around the circle. You may wish to add a turn of duct tape to cover the sharp edges of the screen. With the top bucket's added girth, it's now likely to jam when nested in the bottom bucket. Attach three or four wooden stop blocks to the outside of the sieve. Fashion them from scraps of 1x2 lumber, and drive screws into them from inside the sieve. Place them so the sieve cannot drop far enough into the bottom bucket to jam.

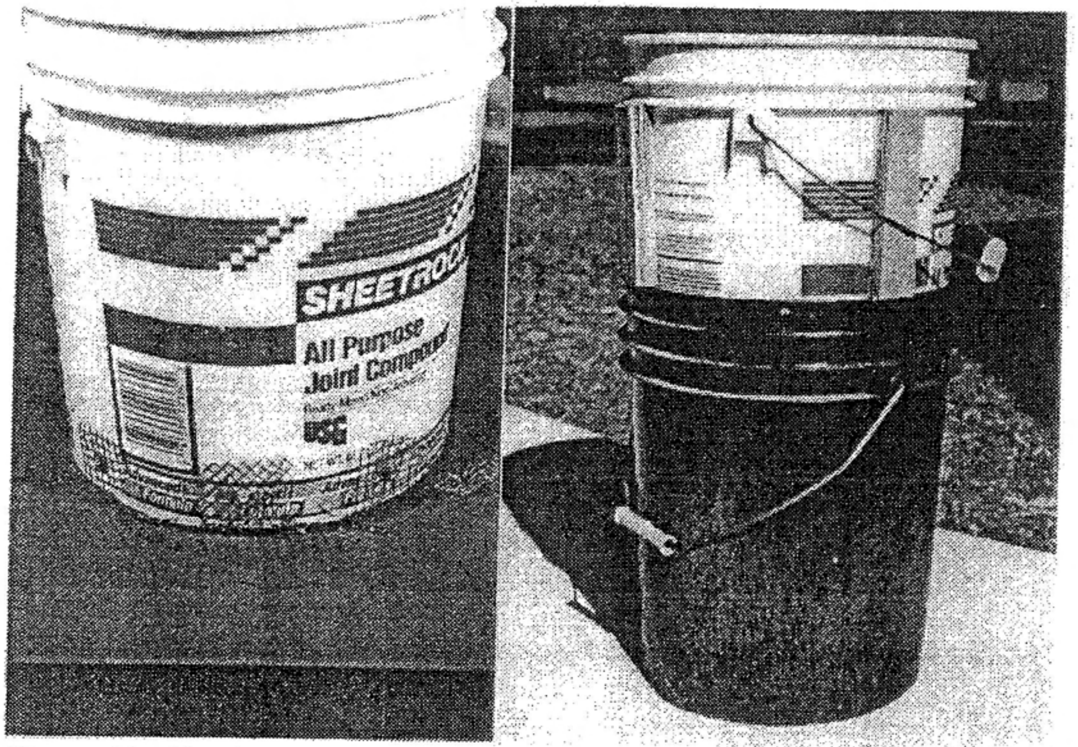


Figure 11 - Pleating the sieve screen, and the nesting stops in place

Nest this strong sieve inside the other bucket, then carefully pour your mill contents into the sieve. Rock and rotate the sieve, rolling the media around to separate the material from the media.

I like having one sieve for carbons and meal powder, one for fuels besides carbon, one for general oxidizers, and one just for chlorates. I wash the sieves which come into contact with oxidizers after each use.

The sieves also serve as good medium washers. Just fill the bottom bucket up past the screen with water or solvent, and swish the media around on the screen. Milling clean sawdust is another good way to clean media -- *but DON'T try to clean media used for grinding chlorates so that you may re-use it for other chemicals -- Always use separate media for chlorates!*

That completes construction of the ball milling system.

Next: Some milling tips and anecdotes from actual use of the mill.

Section 3 -- Using your new ball mill

First and foremost, another safety lecture!

You should start and stop your mill remotely, and keep your hands away from all moving parts while the mill is operating. **You should build the lidded version of the mill, both for noise-suppression, and for personal safety. If you've built a lidless mill, please fashion a pulley guard to cover the 6" pulley and belt, so you cannot accidentally get your fingers caught. Also be aware to avoid the rotating drive shaft -- it can catch hair, clothing, or fingers. Again, having a lid *-closed-* will mitigate that danger.**

A 1/3 HP electric motor has sufficient power to break or even sever a finger if you get caught in the moving parts of this mill. Safety FIRST. NEVER TOUCH THE MILL WHILE IT IS RUNNING!

Hot-glued 1/4" plywood makes an acceptable pulley guard. The best safety feature is a *closed* lid coupled with remote starting and stopping.

On milling mechanics:

Media Charging rates, slippage, lifters, and things which go "clunk".

Some materials are more 'slippery' than others. Waxy substances like stearine or mixtures containing petrolatum (*NEVER* mill whistle mix!) can cause your charge to slip, if you're milling without lifter bars.

Well, you *can* install lifters. However, a simpler solution may be at hand. Try adding more media (and material at a 2:1 balls-to-material ratio), up to about a 65% fill factor. Very often, that is all it takes to stop the slippage.

It's easy to tell when your mill is milling correctly, or if the charge is slipping. When the mill is grinding properly, it gives out a *distinct*, continuous, rattling clatter. It's very loud, and has no significant pauses or peaks.

When a mill is overcharged, or turning too fast, the charge tumbles in 'lumps', instead of cascading. Then, you'll hear the mill make thumping, intermittent noises. It may clatter for a while, then thump, or go quiet for an instant, then clatter again. If you hear intermittent thumping, try reducing your fill-factor a little. Damp, sticky materials will worsen this condition, and may require adding more liquid, or using much heavier media (like switching from ceramic to lead).

It's also easy to tell when a mill's charge is slipping. Instead of, or in addition to the clattering sound, there will be a noticeable "swish, swish" noise, as the balls *slide* down the walls of the jar, rather than fall down the face of the charge. This is a very unique and recognizable noise; you should have no trouble telling when your mill is slipping badly. If it's slipping just a little, you may not know for a while.

Periodically inspect your milling jars. If you notice any grooves running circumferencially around the inside of the jar, you should infer that the charge has been slipping. You may also hear a little 'swishing' behind the louder ball clatter.

Also inspect your jars for cracks or failed glue joints. Milling imposes very strong forces on your milling jars -- they will wear out eventually, and usually fail by cracking. They do last a long time, though -- normally, hundreds of hours. That's a lot of milling.

On milling times:

Don't fall prey to keeping your old ideas about milling times when you use this new, efficient mill. Here's a quick list of comparable times from 'popular' literature, and *actual measured times* for this mill, using one-gallon jars.

substance	popular time	this mill's time
Air-Float Charcoal	over night (10h)	40 minutes
-100 mesh KNO3	four hours	30 minutes
meal powder	up to 72 hours	3 hours

Over-milling just wears out jars and media, without affording you significant improvements in particle sizes. Check your progress frequently, until you're comfortable with how fast this mill works.

On milling temperature:

Milling temperature can play an important role in determining the efficiency and fineness of grind of your mill. Especially with substances which have a lot of water of crystallization, or which are hygroscopic, temperature has a dramatic effect.

Take, for example, an experiment with milling 75-15-10 meal powder. Cool weather afforded an opportunity to see what low temperatures would do to the milling process. For each test temperature, six hundred grams of meal was milled in a one gallon jar under the following circumstances:

Formula : 75-15-10
KNO3 : fertilizer-grade prills, pre-milled 30 min. to 100 mesh.
charcoal : willow, pre-milled 20 minutes to -325 mesh.
sulfur : 95% pure agricultural dusting sulfur, -325 mesh. the 5% 'contaminant' was determined by analysis to be silica (Flow agent? Or was the sulfur ball milled with flint pebbles?)

Material was milled for three hours with 29 lb. of 3/4" x 3/4" lead cylindrical media.

- At 35 F, the powder appeared to mill properly, remained very 'loose' (did not tend to clump), and tested 7.1 seconds average in the PGI "Golf Gun" test.

- At 40 F, no noticeable change from 35F.

- At 65 F, the powder gained speed, shooting 7.7 seconds, average.

- At 75 F, the powder seemed 'clumpy' and adhesive to the touch, but did not tend to agglomerate in the jar. Some slight caking in the jar corners was noted. Golf tests averaged 8.2 seconds.

Obviously, there was a beneficial mechanism at work, here!

- At 90F, the entire charge of powder was found to have caked in a solid lump at the wide end of the jar. Smartly tapping the jar with a dead-blow mallet freed up the lump, which was found to be quite dense (about 1.6 g/cc), but still fairly soft and friable. It was crushed back to fine meal with a mortar and pestle. Golf gun times now averaged 9.5 seconds!

At 90F, the 'lumping' phenomenon was not 100% consistent. Some batches agglomerated, and some, inexplicably, did not. But at 100F, all batches tended to lump -- always at the wide end of the jar. That's a mechanical effect, apparently. The lumping phenomenon does seem to require some moisture to occur, but no water was added -- the only moisture present was in the 'damp' KNO3.

When this 'lump' was corned to FFFa grain size, the powder *averaged* 10.2 seconds with the PGI golf gun.

What's significant about that is this; Goex FFg sporting powder only averages 9.8 seconds! **Imagine -- commercial-quality lift powder for 50¢ a pound!**

Please remember that this was only a test. If you're going to manufacture meal or lift (even for your own use), you need to obtain the necessary local, state, and federal permits to do manufacturing of explosives. *Additionally, it is not recommended that you mill explosive substances in your ball mill, since they could explode from the forces imposed by milling.*

What this experiment shows, though, is that there is a direct correlation between temperature and how well materials can be incorporated in a ball mill. This finding is not really surprising. Commercial mill manufacturers all offer 'heat jackets' for their large mills, so that milling contents may be heated by hot water or steam.

It's possible to use the motor of your mill as a heat source. More on that later. But for now, you need to recognize that the motor may generate undesirable heat. For very short milling runs, the motor's heat is not an issue. Almost all milling tasks can be done in less than an hour with this mill -- meal powder was offered as an example of a *very long milling job* (how many times have your read about milling meal for 24, 48, or even 72 hours?). For long jobs, it may be necessary to add cooling to your lidded mill. That subject is discussed in the 'accessories and improvements' section of this booklet.

On media selection:

Careful selection of media can pay dividends in milling. There are advantages and disadvantages to each media type.

Remember this: For a given size jar, the smaller the media you can use, the faster your milling will go.

If small milling media are heavy enough to grind the materials you're using, they will work better because smaller balls offer more contact points - more 'milling faces' - than larger media.

Lead media is cheap, and it's heavy enough to mill nearly any friable chemicals. Its downsides are that it tends to slightly contaminate powders with a black tinge which can only be assumed to be metallic lead, and that it's not hard enough to mill very hard materials.

The former may mean that smokes from lead-milled powders are more toxic than they might be otherwise. The latter means that lead media is useless for reducing flitter metals and some metal oxides.

> **On hardening lead:** It's generally known that adding antimony metal to lead both increases the hardness of the lead, and decreases the melting temperature. Relatively unknown is that it's difficult to properly alloy the two metals -- typically, it requires a protective method (like a blanket of flux or carbon over the melt, or an inert gas environment) to prevent oxidization of the lead at the high temperature necessary to initially melt the antimony. Fluxes and other metals, like tin, are often added. Tin will also contribute to the alloy's hardness.
>
> Rumors abound that tire weights and bullets are antimony hardened lead. Maybe, maybe not. Don't count on it. Most tire weights are made from *scrap* lead, which may contain anything. Bullet alloys vary in composition, as well.
>
> A simple way to get your lead already hardened is to buy lead-bearing Babbit Metal or Linotype metal. Babbit is used for pouring custom bearings for large engines; some contain zinc or tin, but no lead. Although the pre-made alloys are more expensive than scrap lead, you don't have to perform an alloying step to get harder media.

Ceramic media (and especially high-alumina ceramics) are almost ideal for every type of milling you can do. And they're *expensive*. Oh, well!

Steel balls are very inexpensive, hard, and easy to obtain in bulk. They're dandy for milling just about anything -- except oxidizers, which tend to cause them to rust almost *instantly*, and **anything** which might ignite from sparks. Stainless steel balls are a little more expensive, but corrosion resistant. They tend to spark less than mild steel.

Round flint pebbles do a nice job of milling charcoal and sulfur. Don't use them on any pyrotechnic mixtures, though. Flint is cheap, but it's not very dense, compared to metal or ceramic. Therefore, it's not suited to rapid grinding of very hard materials.

Glass marbles work well for some grinding. Toy store marbles are pretty expensive for grinding media, but they are sold in bulk for just that purpose. There's a rumor afloat that glass demonstrates a piezo-electric effect under impact which might ignite mixtures. That's not proven, but the argument still needs exploring.

Tungsten carbide media is both expensive and very, very hard. It serves well for fine grinding of nearly anything you can't grind with other media. There is a suspicion of sparking here, too, but nothing proven.

Media for mixing:

Your mill can serve as a very rapid mixer, as well as a grinder. Remove the grinding media, and replace it with a small charge (about 25% by volume) of wood, plastic, or rubber rods. The rods should be no longer than 1/3 of the mill jar's inside diameter -- for the one gallon jars, that's around 2 inches long. Half-inch diameter rods work fine. Charge the mill up to 50% full of material, and set it to turning. The rods will tend to 'divide' the mixture as it tumbles.

Even without 'mixing media' the ball mill makes a rapid, effective mixer for powders and low-viscosity liquids.

Remember, for grinding: Use 50%-by-volume media charges, 25%-by-volume material charges. Never under charge a jar, or you'll damage it or the media. Over charging will result in slower milling.

Selection of a milling site:

The natural reaction to this is, "Well, it's going in my shop -- where else?". But that's not always wise.

Mills are just plain *noisy*. Even with sound-deadening liners and a lid in place, this mill makes a loud, unpleasant sound which will quickly grind both powders ***and*** your nerves very fine, indeed.

If you mill mixtures, you also risk fire or explosion. Certainly, for those processes, you want a mill which is remotely located, and remotely started and stopped.

For those reasons, it's a good idea to use a remote milling location. Your 'milling shack' can be as simple as a tent erected on the 'back forty', with a long extension cord, or a small generator. It can be as elaborate as you wish. But you should resist the impulse to make it into a multi-purpose building, since you may then be tempted to work in it while milling is going on. Dedicate the enclosure to milling, only, for safety's sake.

On dead men, hair, and jewelry:

No matter how frequent the warnings, someone will eventually get their sleeve, hair, or watchband caught in a running mill -- it's inevitable. And it would happen whether it was this mill, or a commercial one. Mills are machines, and people end up getting wound-up in machines, no matter how much you preach safety. **So here's a suggestion to help minimize the danger.**

In addition to whatever method you use to **remotely** turn power on and off for this mill, *also add a "dead-man switch"*. The classic 'dead-man' arrangement has to be held down by a user, or it will switch off. Rather, what is called for here is a LARGE, easy-to-flip, easy-to-see switch mounted right in the middle of the front skirt of the mill. That way, the switch will be accessible by your 'free' hand if you should get the other hand (or head, or foot) caught in the moving parts of the mill. Please resist the temptation to use this special switch for turning the mill on and off -- use it JUST as a safety cutoff.

Installing an "interlock" switch on the lid is helpful. An interlock consists of a spring-loaded switch which *does* have to be held down to stay closed. This switch is held by the lid. If you open the lid, the mill turns off. Simple.

You *did* build the lidded version of the mill, didn't you?

On static electricity:

Some pyrotechnicians have expressed a concern about using plastic milling jars, because of their fear that the jars might generate static electricity, and subsequently cause sparks. Of course, the fear is that the sparks might ignite whatever they were milling.

It is true that PVC is a material in the tribo-electric series. That is, it can generate static when exposed to friction. But it is my opinion that this fear of static during milling is unfounded. Here's why:

Each milling jar is a closed system when its lid is in place. Any charge between items inside the jar will:

1) have to **come from the contents of the jar, because it is a closed system,** and
2) tend to be equalized over time by
    a) the mixing action in the jar, and
    b) by the fact that most pyrotechnic mixtures are slightly conductive.

My opinion is that there is virtually no chance for sparks from static electricity to develop inside the jar while milling is going on.

It is true that the *whole jar* might develop a charge, relative to the rest of the mill. But that is only a danger if there is explosive milling waste around the mill mechanisms. For that reason, it's wise to keep your mill clean.

Also, a charged-up jar might cause a spark to form between itself and your body. For that reason, you should touch the body of the jar before you remove the cover. That way, any accumulated charge between you and the jar will be equalized before you expose the jar's contents.

The solution to that last problem is simple. If a conductive metal brush is bonded to an earth ground, and to the moving parts of your mill, and if that brush is allowed to lightly rub the outside of the moving jars, then no charges will be accumulated. If the rubber covers on the ball-bearing rollers are eliminated, its only necessary to ground the rollers. They will drain charges from the jars as they roll.

That's a pretty extreme solution, actually. I believe that it *might* be necessary only in desert or arctic conditions, where the air is perpetually very dry. In most climates, static does not tend to accumulate on the jars, at all, except during the winter months, or in excessively air-conditioned buildings.

Please understand, that on this whole issue of static, these are just **my opinions. You should research the subject to your own satisfaction.**

On safely emptying your jars:

When you're done grinding a charge, you have to separate the material from the media. The real problem here is that you're dealing with a very fine (usually combustible -- or even *explosive*) dust. It floats into the air, wafts up your nose, into your clothing, around your shop... simply put, it can be a *mess*!

For those reasons, you should always wear breathing protection when emptying your mill jars. Also take care to very gently and slowly pour the jars' contents into the separation sieve. Then, as soon as the contents are in the sieve, put the cover on the top sieve bucket (that's why the instructions said, "the top bucket should have a lid").

Don't shake your sieve, but rather, tip it up onto one edge of its base, then vigorously *roll* it around, in a sweeping motion. The media balls will sweep around the sieve in a circular pattern, rolling over one another as they do, and very effectively (and quickly) scrubbing all the mill contents through the screen.

Use a large funnel to guide the milling media back into the jars. On the one gallon jars, pour the media out of the sieve slowly and from as low a height as possible. The media balls are heavy, and they could crack the bottom of the jar, if dropped too hard. If you have the patience, *place* them individually back into the jar, rather than pouring them in.

Then scoop the milled material from the lower sieve bucket, rather than trying to pour it out. Pouring will almost always result in a lump of powder falling out unexpectedly, and "splashing" fine powder everywhere. This is especially unpleasant when the mill contains fine carbon.

How vigorously you sieve will determine how long before the sieves wear out. If you can, get woven hardware cloth for your screens, rather than screen which has been lap-soldered in the galvanizing process. The woven screen lasts about ten times as long as parallel-laid screen. 'Flat laid' or parallel laid screen lasts about thirty or forty hearty screenings. (still, it's very inexpensive) Woven screen lasts for hundreds of uses.

On milling metals:

I must say that I do not recommend milling metals in this mill. That's something better suited to very large commercial mills. Powdered aluminum and magnesium are quite inexpensive compared with the time and trouble you'll go through to mill your own flake. People who mill their own flake usually start with shredded foil or atomized metal, use tungsten carbide or high-alumina media, and use a suspending fluid like mineral spirits or denatured alcohol to keep the metal particles from re-welding during milling.

This is just not a task well suited to the amateur, and I don't recommend it. The suspending fluid might leak from the jars, causing a fire or explosion hazard. The milling takes *forever* -- it takes about ten times as long to get from twenty micron particles to six micron particles as it did to go from foil chunks to twenty microns. Additionally, the amateur has no effective way to grade the material after grinding. No -- this is one material you ought to buy, rather than make... in my opinion.

Section 4 - Improvements to the mill

No amateur project is ever finished. Just as soon as you've used your mill to mill "one of everything" in sight, you'll begin to see ways you could improve it. Here are a few ready-made ideas. Some are from my own mill's evolution, and some are suggestions made by readers of the original articles.

A thermometer:

Well, SURE! If temperature is important to milling, then it would be nice to know what temperature it is inside there. I bought a $7.00 refrigeration service thermometer for the purpose. It's a 1" diameter dial thermometer with a 4" long sensing stem. I drilled a 5/32" hole in the front panel of the lid (right about at jar level), and stuck the stem in through the hole.

(So, Mr. Author... How do you inspect the thermometer when you're not supposed to be in the room with the running mill, huh?) Well, I ... uh... I...(blush!)

OK... so I can't, and still follow my own safety rules, but here's how to be sure what the temperature is, *all the time*.

A thermostat:

Yes, you read right. I don't like variables; temperature was one I knew affected the quality of my milling. So I installed this fairly elaborate way to make sure the temperature of my mill remained constant.

The mill's motor makes a fine heat source. The way the cabinet is built, warm air from the motor rises right up through the six-inch pulley's cutout into the milling area in the lid.

I installed a junk thermostat (air conditioning type, not heating) at jar level on the rear panel of the lid (inside the lid, of course!). Now, such thermostats aren't designed to switch 110VAC, but I'm using the thermostat to *directly* control the power to a very small muffin fan. It draws so little current, it doesn't appear to be harming the thermostat's mercury switch. You might require a relay to handle the fan's current.

I placed the fan in the lower-left corner of the lid, with a hole cut in the lid so the fan can **draw in** cool air. It forces this cool air into the lid, which forces hot air back down the pulley hole on the right end of the milling deck.

I set the thermostat at 95F, and it seems to control the temperature very accurately. Actually, the temperature inside the cabinet varies about twenty degrees up and down. But the filled jars provide a large heat sink, and they stabilize at the average air temperature inside the lid.

A timer:

A simple way to 'remotely' start and stop your mill is with an inexpensive appliance timer. Such timers cost under $10, and usually time over a 24 hour cycle.

With that capability, they're not very accurate for short timing. In fact, most of them cannot be set for an 'ON' or 'OFF' cycle shorter than one hour. A light, also plugged into the timer, and mounted where it can be easily seen from outside the milling building can serve as an indicator that the mill is running. Usually, though, you'll be able to *hear* the mill, even if you're some distance away from it.

If you use such a timer, be sure to unplug it after it turns the mill off. Otherwise, your mill will come on again in 24 hours.

(author's note -- Neighbors just *love* this effect. They especially like it if they know you're away at a pyrotechnics convention, and this ***weird sound*** starts coming from your back yard every day at the same time.)

Quick-release jar lids:

I'm personally quite happy with my rubber test caps for jar lids. However, I seldom use 4" jars, except for formulation experiments. With the 4" jars there is an issue of the clamp interfering with the jar's rolling. To solve that, one reader offered an improved lid. The following diagram shows his design.

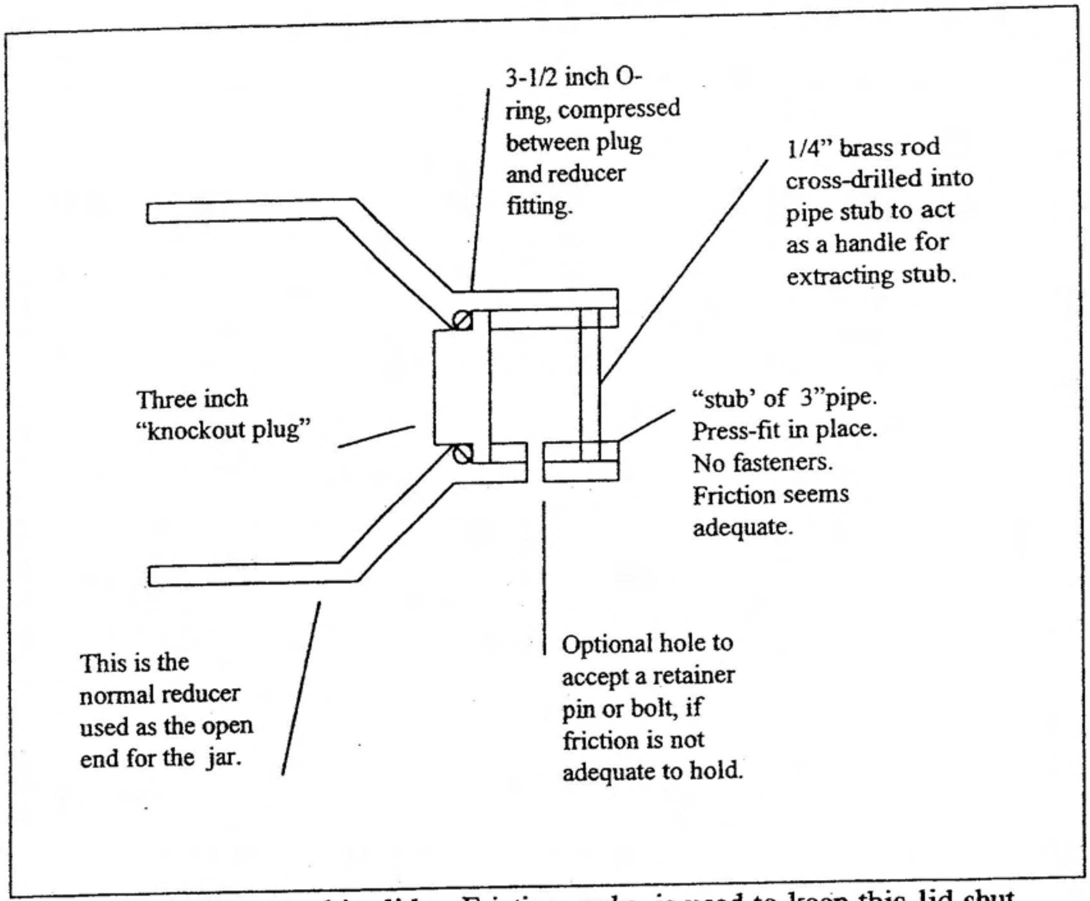

3-1/2 inch O-ring, compressed between plug and reducer fitting.
1/4" brass rod cross-drilled into pipe stub to act as a handle for extracting stub.
Three inch "knockout plug"
"stub' of 3"pipe. Press-fit in place. No fasteners. Friction seems adequate.
This is the normal reducer used as the open end for the jar.
Optional hole to accept a retainer pin or bolt, if friction is not adequate to hold.

Figure 12 - Improved jar lids. Friction, only, is used to keep this lid shut. An O-ring provides the seal. (Design, courtesy of Duane Owens)

Credits

I have sincerely enjoyed developing this mill, and exchanging ideas with other pyrotechnicians around the world. A number of companies and individuals supplied information to satisfy my research. Among them:

Technical information about milling theory and methods was provided by:

- Paul O. Abbe Inc., manufacturers of ball milling equipment

- E.R. Advanced Ceramics, a division of U.S. Stoneware, manufacturers of ball milling equipment

- Epworth Manufacturing Company, Inc., manufacturers of EMCO mills and milling media.

- McMaster-Carr Industrial Supply Co., suppliers of industrial materials

- Fisher Scientific

- Grainger, suppliers of industrial equipment

Suppliers of commercial milling media:

Paul O. Abbe, Inc.	(201) 256 4242
Adolph Coors Corporation	(800) 648 0800 *
Epworth Manufacturing Company, Inc.	(888) 566 9021 (toll free) *
E.R. Advanced Ceramics (U.S. Stoneware)	(216) 426 9433
Fisher Scientific	(800) 766 7000

(* low-cost sources)

Ball milling knowledge was shared by:

Guy Lichtenwalter, Murr Rhame, Tom Perigrin, Bill Nelson, Frank Heasley, Paul Judd, Duane Owens, and Tom Dimock.

My thanks go to each of these companies and individuals for their helping me in my research.

I wish you long service from your new mill. L.E.S.